

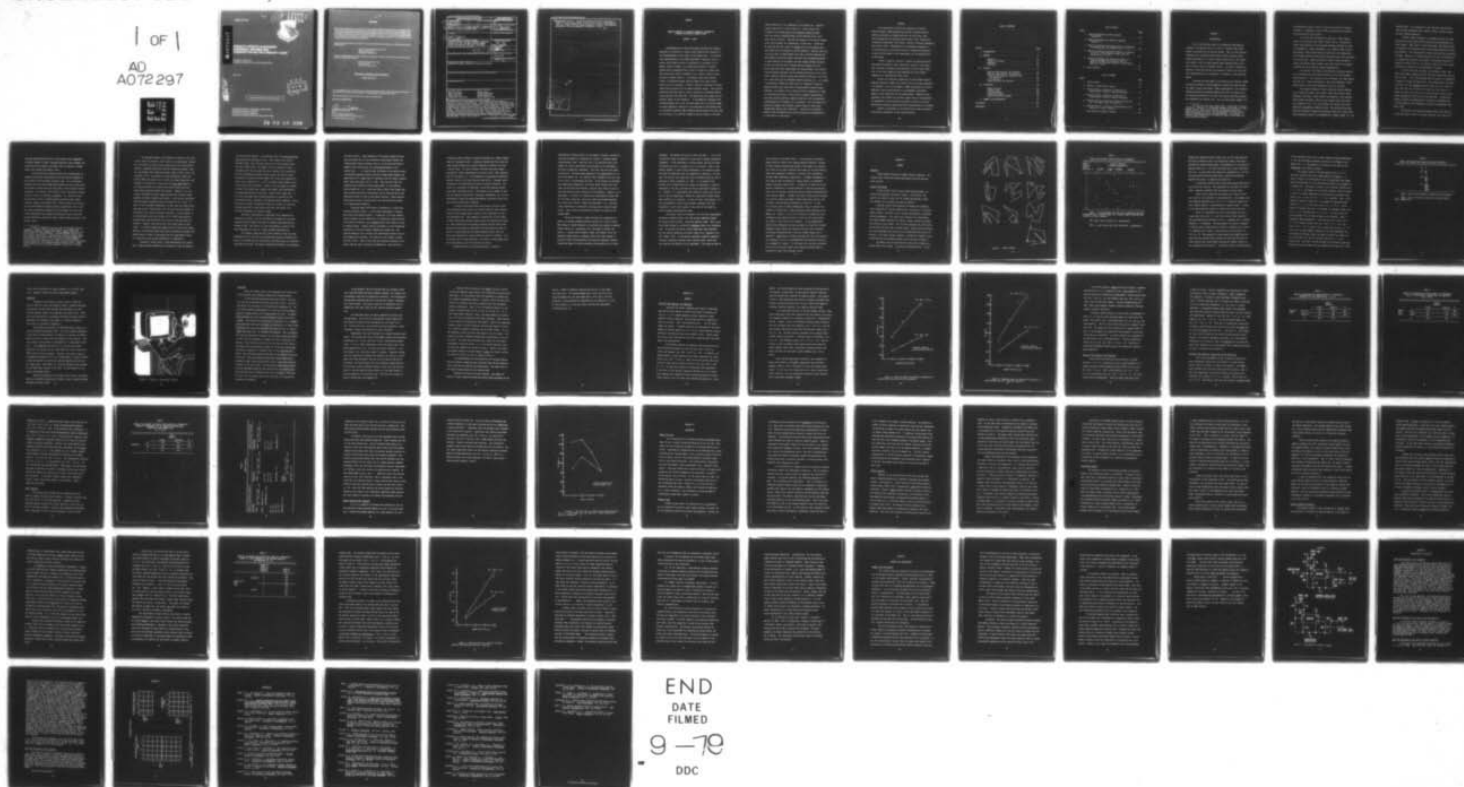
AD-A072 297

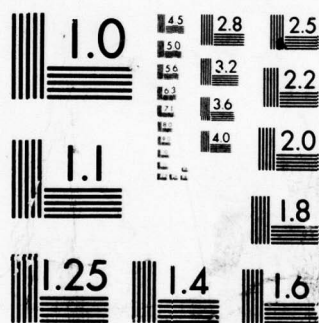
AEROSPACE MEDICAL RESEARCH LAB WRIGHT-PATTERSON AFB OH F/G 5/2  
MODALITY EFFECTS IN SCANNING NONVERBAL INFORMATION: EVIDENCE FO--ETC(U)  
JUN 79 R L HANN  
AMRL-TR-79-53

NL

UNCLASSIFIED

1 OF 1  
AD  
A072 297





MICROCOPY RESOLUTION TEST CHART  
NATIONAL BUREAU OF STANDARDS-1963-A



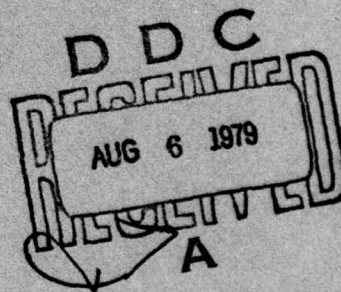
AMRL-TR-79-53



**MODALITY EFFECTS IN SCANNING  
NONVERBAL INFORMATION:  
EVIDENCE FOR MULTIPLE MEMORY CODES**

REUBEN L. HANN, Ph.D.  
AEROSPACE MEDICAL RESEARCH LABORATORY

June 1979



Approved for public release; distribution unlimited.

AEROSPACE MEDICAL RESEARCH LABORATORY  
AEROSPACE MEDICAL DIVISION  
AIR FORCE SYSTEMS COMMAND  
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

79 08 03 028

AD A 072297

DDC FILE COPY

## NOTICES

When US Government drawings, specifications, or other data are used for any purpose other than a definitely related Government procurement operation, the Government thereby incurs no responsibility nor any obligation whatsoever, and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise, as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

Please do not request copies of this report from Aerospace Medical Research Laboratory. Additional copies may be purchased from:

National Technical Information Service  
5285 Port Royal Road  
Springfield, Virginia 22161

Federal Government agencies and their contractors registered with Defense Documentation Center should direct requests for copies of this report to:

Defense Documentation Center  
Cameron Station  
Alexandria, Virginia 22314


## TECHNICAL REVIEW AND APPROVAL

AMRL-TR-79-53

This report has been reviewed by the Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER



CHARLES BATES, JR.

Chief

Human Engineering Division  
Aerospace Medical Research Laboratory



REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AMRL-TR-79-53	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER 9
4. TITLE (and Subtitle) MODALITY EFFECTS IN SCANNING NONVERBAL INFORMATION: EVIDENCE FOR MULTIPLE MEMORY CODES.	5. TYPE OF REPORT & PERIOD COVERED Doctoral Dissertation Thesis	
7. AUTHOR(s) REUBEN L. HANN, Ph. D.	6. PERFORMING ORG. REPORT NUMBER	
9. PERFORMING ORGANIZATION NAME AND ADDRESS AEROSPACE MEDICAL RESEARCH LABORATORY, AEROSPACE MEDICAL DIVISION, AIR FORCE SYSTEMS COMMAND, WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433	8. CONTRACT OR GRANT NUMBER(s)	
11. CONTROLLING OFFICE NAME AND ADDRESS 1274p. 11	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 16 17 62202F, 7184-14-07	
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	12. REPORT DATE June 279	
	13. NUMBER OF PAGES 74	
	15. SECURITY CLASS. (of this report) Unclassified	
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE N/A	
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Modality Effects                      Memory Coding Short Term Memory                  Sternberg Paradigm Memory Scanning                    Sensory Modality Information Processing              Choice Reaction Time		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The purpose of this experiment was to study memory coding processes as a function of input sensory modality. Some investigators have proposed a single auditory/articulatory code, regardless of stimulus modality, while others have suggested that multiple sensory-specific codes are generated. Subjects in this study learned to associate 10 twelve-sided random polygons with ten complex sounds. These paired associates were then used in several versions of a Sternberg binary choice reaction time task. Results indicated that subjects were able to maintain sensory-specific memory information when it was		

advantageous to do so. The observed effects were best interpreted in terms of a multiple-code model, in which both a primary (same-modality) code and a weaker associate (opposite-modality) code are simultaneously generated as the to-be-remembered information is input.

Accession for	
NTIS GMAI	
DDC TAB	
Unannounced	
Justification	
By	
Distribution/	
Availability Codes	
Dist.	Avail and/or special
A	



## **SUMMARY**

### **MODALITY EFFECTS IN SCANNING NONVERBAL INFORMATION: EVIDENCE FOR MULTIPLE MEMORY CODES**

**REUBEN L. HANN**

Investigations into short-term memory encoding and scanning processes as a function of sensory input modality have resulted in two interpretations of the nature of the memory code: (1) multiple code representations, with format depending on modality, and (2) a single code system in which all information is converted to one format, usually thought to be auditory/articulatory in nature. Studies which interpreted their results in terms of a single code have always used "verbal" materials (e.g., digits, letters, words, pictures of common objects). The present study used nonverbal stimuli to determine whether subjects might alter their coding habits in such a situation. Subjects learned to associate 10 twelve-sided random polygons with 10 complex auditory sounds. These paired-associates were then used in several versions of a Sternberg binary choice reaction time (RT) task. The memory sets were either all one modality (pure) or mixed-modality. In the Modality Irrelevant (MI) condition probes could occur in either mode, and, if positive, might be either physically identical or the associate of the matched item. In the Modality Relevant (MR) condition similar memory sets were used but the probe, if it matched a memory item, was always in the same

format (modality) as its appearance in the memory set. Negative probes could occur in either condition. Eight subjects participated in all conditions of the repeated measures design; half the subjects performed under the MR condition first, half under the MI condition. Mean RTs were faster for MR than MI probes, using similar memory set compositions in both cases. Within the MR condition RTs were faster for mixed than for pure memory sets; this effect was not obtained in the MI condition. The fact that subjects were able to reduce memory scan time in the MR condition for both auditory and visual probes indicates that information specific to input modality of the memory item was somehow encoded and maintained, and could be used to reduce effective memory set size. Error rates were three times higher for associational (cross-modal) than for physical matches; the MI condition had twice as many errors as MR. Overall, positive probes were 50% more error-prone than negative, while there was no difference between auditory and visual probes. A "translation" effect was noted; that is, responses to physical identity probes were faster than to associational identity probes. Generally, the results of this study were best interpreted in terms of a multiple-code model, in which both a primary (same-modality) code and a weaker associate (opposite-modality) code are generated simultaneously as the memory set is presented. RT to the probe is a function of memory item strength, primary modality items being checked more rapidly than associates. Faster RTs for auditory probes in the MR condition were noted and possible interpretations of this effect are discussed.



## PREFACE

This dissertation research was conducted in Systems Research Branch, Human Engineering Division, Aerospace Medical Research Laboratory at Wright-Patterson Air Force Base, Ohio. The investigation was performed under Project 7184, "Man-Machine Integration Technology," Task 718414, "Operator Workload Assessment," and Project 2313V1, "Fundamentals for Man-Machine Integration." It was submitted to the Graduate School of Vanderbilt University in partial fulfillment of the requirements for the degree Doctor of Philosophy.

I wish to thank Dr. Richard L. Blanton, my major professor and committee chairman, whose inspiration, patience, and support were invaluable throughout the preparation of this study; thanks also to the other members of the committee for their helpful suggestions in preparing the final draft.

Without the extensive cooperation of the Aerospace Medical Research Laboratory (AMRL) this research would have been impossible. I am indebted to all my colleagues at AMRL--especially Dr. Donald Topmiller, whose understanding and encouragement contributed greatly to the completion of this dissertation. Thanks are also extended to Bill Brandt for software support and to Tony DeFrances for assistance in the statistical analysis, as well as the many discussions concerning implications and interpretations of the data.

Finally, my gratitude to Pat Burns for her usual thoroughly professional preparation of the typed manuscript.

# TABLE OF CONTENTS

Chapter	Page
I. INTRODUCTION	1
II. METHOD	12
Subjects	12
Stimuli and Design	12
Apparatus	18
Procedure	20
III. RESULTS	24
Reaction Time Analysis, MI Condition	24
Reaction Time Analysis, MR Condition	28
Reaction Time Analysis, Between MI and MR Conditions	29
Error Analysis	32
Serial Position (SP) Analysis	35
IV. DISCUSSION	38
Memory Set Size	38
Response Type	38
Serial Position	40
Translation Effect	42
Modality-Specific Encoding	44
V. SUMMARY AND CONCLUSIONS	54
APPENDICES	58
REFERENCES	65



## LIST OF TABLES

Table	Page
1. Visual and Auditory Paired-Associate Assignments . . . . .	14
2. Memory Set Composition, Modality Relevant Condition . . . . .	17
3. Mean RT to Auditory and Visual Probes as a Function of Response Type, MR Condition ( $\underline{s}$ = 1 to 4) . . . . .	30
4. Mean RT to Auditory and Visual Probes as a Function of Pure Vs. Mixed Modality Memory Sets, MR Condition ( $\underline{S}$ = 2 to 4) . . . . .	31
5. Mean RT to Auditory and Visual Test Probes as a Function of Modality Irrelevant (MI) Vs. Modality Relevant (MR) Condition, Mixed Memory Sets ( $\underline{s}$ = 2 to 4) . . . . .	33
6. Error Analysis . . . . .	34

## LIST OF FIGURES

Figure	Page
1. Visual Stimuli . . . . .	13
2. Subject at Experimental Console . . . . .	19
3. Reaction Time as a Function of Physical Vs. Associational Identity; Positive Responses . . . . .	26
4. Reaction Time as a Function of Physical Vs. Associational Identity; Negative Responses . . . . .	27
5. Reaction Time as a Function of Serial Position for $\underline{s}=4$ , Pure Memory Sets, MI Condition . . . . .	37
6. Reaction Time as a Function of Probe Modality; MR Condition, Positive Responses . . . . .	50
7. Tone Generator Schematic Diagram . . . . .	59

## CHAPTER I

### INTRODUCTION

One of the principal goals of contemporary psychological research is to discover what it is that is "learned" when information is processed by our sensory systems. That is, what stimulus attributes are retained and what form do these attributes take? Modern psychologists, of course, cannot accept Plato's "wax impression" theory, with its heavy emphasis upon representation in the form of direct copies of external reality. In order to explain our ability to store and retrieve vast amounts of data it is clear that this information must be transformed, or encoded, in some efficient manner.

Following the development of the Peterson and Peterson (1959) distractor technique, research emphasis shifted from long-term memory (LTM) to short-term memory<sup>1</sup> (STM) considerations. The Petersons' rehearsal prevention procedure demonstrated that, if stimuli were not actively processed for the first few seconds following exposure, the information was rapidly lost. This critical period seemed to be

---

<sup>1</sup>In this text the words "short-term," "long-term," "active," "inactive," "primary," or "secondary" memory are all used in an operational sense. They are not intended to imply any particular theoretical position; rather they are descriptive of the types of tasks as defined a priori by the experimenters. The single- vs. multiple-store memory issue is beyond the scope of this paper and can be pursued elsewhere.



the appropriate point at which to pursue the problem of stimulus encoding. A tremendous volume of STM investigation had followed and continues until the present.

Two early STM investigations, Sperling's (1963) sensory decay rate experiment and Conrad's (1964) acoustic confusability study, both pointed to an articulatory-auditory encoding of stimulus information. Other researchers (e.g., Murdock, 1969; Frisoe and Blanton, 1970) reached similar conclusions, even though they used stimulus materials which should have been more easily processed as a visual code. Adams and Dijkstra (1966), Posner and Konick (1966), and others found, however, that their results could not be accounted for by an auditory coding interpretation.

The advent of the binary classification technique resulted in an increased level of research activity in the area of memory coding processes. Two versions of this technique, the Posner matching task (e.g., Posner and Mitchell, 1967) and Sternberg's (1966) memory scanning task, have generated the bulk of the data.

The general outcome of studies using the Posner technique (e.g., Posner and Keele, 1967; Posner, 1969, 1970; Posner, Boies, Eichelman, and Taylor, 1969; Clement and Carpenter, 1970; Dainoff, 1970; Dainoff and Haber, 1970) was that stimuli which were physically identical (e.g., A-A) were matched more rapidly than those which were conceptually identical (A-a). The conclusion was that physically identical stimuli are matched by means of a visual code, while conceptual identity is determined by a "name" lookup, i.e., an

auditory code. It is important to note here that the materials used in these experiments were "verbal" (digits, letters, words) and were visually presented.

Tversky (1969) attempted to circumvent the bias of verbal materials by using cartoon "faces" paired with pronounceable nonsense "names." Wood (1977), on the other hand, used verbal materials (letters), but presented them in two sensory modalities (visual and auditory). The conclusions of Tversky and Wood were essentially the same: Subjects in a Posner matching task code the information in a manner which minimizes the amount of processing necessary to complete the match; that is, the subjects could alter their coding strategy as a function of the experimental situation.

As with the Posner technique, the Sternberg (1966, 1967, 1969, 1975) memory scanning task has been used extensively over the past 15 years. It has the advantage that the amount of information in memory is varied (the memory set), thus enabling one to develop a reaction time (RT) function based on memory set size. One can then infer from the RT function the amount of time required to encode the probe (contained in the zero-intercept) as well as the memory scanning rate (the slope of the function). Differential changes in these two parameters are then used to determine the locus of effect as some independent variable is manipulated (see Hann, 1973).

The majority of Sternberg paradigm studies have been concerned with memory search or scanning processes, and, while not



ignoring coding processes per se, dealt mainly with independent variables thought to affect scanning processes, such as memory set presentation rate (Burrows and Okada, 1971) or fixed vs. varied memory sets (Briggs and Johnsen, 1972).

The most relevant Sternberg studies for consideration in planning the present investigation were those which attempted to deal directly with the memory encoding issue. As in the Posner matching task, this was accomplished through the use of items from two stimulus classes which are associated, either through extensive experience: A=a (Peters, 1974; Posner, 1973), noun=picture (Young and Juola, 1977), or arbitrary assignment: A=1 (Clifton, Cruse, and Gutschera, 1973), 16-sided random polygon=two-digit number (Swanson, Johnsen, and Briggs, 1972). These studies, and virtually all the same-different matching studies, except Wood (1977), used the visual presentation modality<sup>2</sup> for both memory and test items. A few investigators have compared associations across visual and auditory modalities (Chase and Calfee, 1969; Kirsner and Craik, 1971; Burrows, 1972).

---

<sup>2</sup>"Mode" or "modality" has been used in two senses (no pun intended). Tversky (1969) and many others, for example, have manipulated "modality" within a particular sensory "modality" (e.g., visual words vs. visual pictures). Perhaps "format" would have been a better choice here. Alternatively, Chase and Calfee (1969), for example, used stimulus pairs which were compared between two sensory "modalities" (e.g., visual letters vs. spoken letters). Since there may be differences in coding processes within and between sensory modalities, the intended meaning of these words--as they occur in this text--has been made apparent explicitly or through context.

As one might predict, the findings of studies in this area are not clear-cut; however, there seems to be considerable evidence for an increase in slope (slower scanning rate) for associational identity, compared to physical identity conditions (Swanson, Johnsen, and Briggs, 1972; Chase and Calfee, 1969; Clifton, Cruse, and Gutschera, 1973). In addition to slope differences, Chase and Calfee (1969) and Swanson et al. (1972) also found significant differences in intercept as a function of the test probe modality. For Chase and Calfee the stimuli were visual letters and their spoken names (auditory probes were faster). Swanson et al. used visually presented two-digit numbers paired with 16-sided random polygons (two-digit numbers were faster). Note that one experiment used both sensory modalities while the other was all visual. In spite of this procedural difference, in both cases the probes which were more easily "verbalizable" were also more quickly encoded, as indicated by the lower RT function intercepts. In this regard, it is interesting to note that Clifton et al. (1973) found physical-associational slope differences but failed to find intercept differences. However, they used visual letter-digit pairs as associates. It could be argued that both letters and digits are highly familiar, over-learned items which could conceivably be encoded with similar ease--at least to the extent that the experimental design is insensitive to any slight differences in "codability."

Conversely, Peters (1974), in the STM portion of an experiment, found intercept differences, but parallel slopes for physical



and associational matches. He attributed this to the mixed positive set presentation technique he used. (The stimuli were visually presented upper- and lower-case letters as in the original Posner and Keele [1967] work.) The memory set was a mixture of these, a technique which had only been used once (Burrows, 1972) previously. With this presentation method, Peters argues, the subject cannot automatically recode the entire memory set as has been suggested by others (e.g., Swanson et al., 1972) to explain slope changes in the associational match condition. Rather, since the memory set format is mixed, the subject must consider each memory item individually, following presentation of the probe. Peters (1974) shows that, in his study, one additional recoding operation is required in the associational match, compared to the physical match condition. Since this adds a constant (estimated by Peters at 19 msec.) to the associational match RT at each positive set size, the result is an intercept difference but parallel slopes.

The above investigations, regardless of the apparent discrepancies in results, can all be offered as evidence for an encoding process which outputs two forms of stimulus representation for storage in STM. The results of a few investigators, however, have been interpreted in terms of a single encoded representation.

For example, Young and Juola (1977) failed to find any slope differences at all, and the only significant intercept difference was noted in the faster RTs for the physical word match condition (word-picture pairs were used). The authors experienced difficulty in accounting

for their results. They summarized, "The present authors believe that the answer lies in the associative relationship between the stimulus-form classes involved, that is, in the ease with which a member of one class elicits its corresponding member in the second class. . . .It could be that the degree of associative learning involving familiar objects and their common names promotes the rapid access of a common name or conceptual code for either stimulus form" (Young and Juola, 1977; p. 136). They also felt that the observed slope differences when using stimuli in two different sensory modalities (e.g., Chase and Calfee, 1969)--even though they were of high associative relationship--can be accounted for by the additional coding in terms of perceptual features. These features would provide salient characteristics not available when working in a single sensory modality.

Young and Juola (1977) made no references to a study done earlier by Burrows (1972). In this study (Experiment 1) stimuli were visual and auditory digits. In addition to the four combinations of memory and test modalities, two additional conditions were run in which the memory set was mixed modality with either a visual or auditory probe. Burrows found no intercept or slope differences between any of the experimental combinations except one: the auditory-auditory (A-A) condition was significantly faster than all other memory-test pairings. The result is very similar to Young and Juola (1977). Recall they found the word-word condition to be faster than any other word-picture combination. Young and Juola



interpreted their findings in terms of encoding of a single "common name" or "conceptual code." Similarly, Burrows felt his study provided strong evidence for stimulus encoding in auditory (or articulatory) form. In terms of theory, Burrows noted that Crowder and Morton's (1969) "precategorical acoustic store" (PAS) seemed to best fit the data; i.e., the information is maintained in modality-specific stores for a brief time and then fed to a "logogen" which categorizes the information and extracts semantic features. The theory is a refinement of Sperling's visual and auditory sensory store model mentioned earlier. Both models are an attempt to deal with the apparent superiority of auditory information; but, as also noted before, under the proper experimental conditions visual storage can be as efficient as auditory.

It should be mentioned here that Kirsner and Craik (1971) also interpreted their results (A-A faster than all other combinations) via the logogen model; however, their experiment was not a true Sternberg task. They employed a constant set size of eight, in order that serial position effects could be examined more closely. They inferred the total memory scanning time for each serial position of each modality combination by subtracting the time required to simply name the test probe (naming latency) from the total time required for a yes-no decision (decision latency). A-A was faster at all serial positions. Of course, scanning rate could not be determined, since set size was not varied.

Burrows (1972), in a second experiment, created an

experimental situation which, in this author's opinion, provides an excellent technique for examining the single vs. multiple memory representation issue. Both pure (A-A, V-V) and mixed (M-A, M-V) memory set--probe combinations were presented as in Experiment 1, but with an important difference. This time, when the test probe was positive, the probe always appeared in the same modality as it had in the memory set. The subjects were informed of this fact and told to use it in performing the task. If the subject was provided this additional information, the search should require less time under the multiple code theories, since he could limit his scan to the items which had been presented in that modality. However, as in Experiment 1, the pure A-A condition was significantly faster than all the other conditions, which once again were grouped together with similar RTs (similar slopes and intercepts); i.e., the additional information in Experiment 2 did not aid in speed of recognition. Again, Burrows interpreted the results in terms of the logogen model.

Morton and Crowder's (1969) PAS model was formulated originally to explain observed auditory superiority in recall tasks. When using all verbal materials--or pictures with readily accessible verbal labels--in a recognition task, the model is useful, but limited. A recent study (Vinglis, Blake, and Theodor, 1977) has produced evidence that, in general, short-term recall memory is basically verbal and dominated by the auditory dimension, whereas recognition memory is mainly nonverbal and dominated by the visual



component. The authors are quick to point out that . . . "it is not claimed that verbal information is never used in making recognition judgements. If the experiment is biased enough, the use of verbal information can be just as great as it is in recall. What is suggested, however, is that verbal information is not necessary under the kinds of conditions used in recognition or detection. Furthermore, the results also imply that visual information may be used in arriving at recall responses" (p. 150). It is possible that Burrows' use of verbal materials (digits in Experiment 1, words in Experiment 2) may have provided the "bias" described by Vinglis et al. Further, it is unfortunate that different stimuli were used in each of the two experiments, making any comparisons between experiments difficult to interpret. In spite of these shortcomings, it is this investigator's opinion that Burrows' approach, with some alterations, can be quite useful in the study of the single vs. multiple memory representation issue.

The present study was designed to use the basic experimental framework of Burrows (1972), but with several important changes. The stimuli were nonverbal visual and auditory items. This is the first known attempt to use nonverbal auditory stimuli in a Sternberg task. In the past the visual stimuli might have been nonverbal, but the auditory associate was always verbal (e.g., Swanson et al., 1972; Dumas, 1972). In the present experiment subjects learned to associate arbitrarily matched visual-auditory pairs, which were then used for the duration of the experiment. The study was done in

two sections as in Burrows (1972). In one section the positive probes could be either in the same or opposite modality, relative to their original presentation format in the memory set; positive test items in the other condition were always in the same modality. These were designated as Modality Irrelevant (MI) and Modality Relevant (MR) conditions, respectively. If memory information in this type of task is encoded in a single format, no difference between conditions should exist. If subjects can make use of the modality information in the MR condition to speed the processing time, then the theories of modality-specific memory representations would receive support. Further, the slope of associational matches (V-A and A-V) should be steeper (longer processing time per item in memory) than the physical matches (A-A and V-V). If only A-A is faster than all other combinations, then it could be considered as evidence for a single auditorily-based encoding of the memory set. Finally, it will be of interest to examine the zero-intercepts of the auditory probe (A-A and V-A) and visual probe (V-V and A-V) data from the MI condition. It was hypothesized earlier that differences in zero-intercept as a function of probe "modality" might reflect the relative ease with which auditory/articulatory representations of the two stimulus groups can be generated. Both groups of stimuli developed for this investigation were designed to be of low meaningfulness and therefore resistant to development of "names." To the extent that this was successful, the two sets of stimuli should yield similar encoding times as reflected by equal zero-intercept values.



## CHAPTER II

### METHOD

#### Subjects

Eight female university students served as subjects. All subjects were trained and tested individually and were paid for their services.

#### Stimuli and Design

Visual stimuli were 10 twelve-sided random polygons, selected from Vanderplas and Garvin (1959, p. 150 and 152); the figures were chosen to have low "C" (verbal description) values. The complete set of stimuli are shown in Figure 1.

Auditory stimuli were generated by mixing five different audio frequencies in various combinations, resulting in 10 distinct complex sounds. See Table 1 for a detailed description of auditory stimulus parameters. The sounds were designed to be unpronounceable and extremely difficult to imitate; subject opinions confirmed the success of this intent. The 10 random polygons were arbitrarily paired one-to-one with the 10 complex tones. These paired-associates were used throughout both sections of the experiment and across all subjects. The visual stimuli numbered 1 through 10 in Figure 1 were paired with the like-numbered complex tones described in Table 1.

The memory sets were generated by using the ten digits in a random number table lookup. The general constraints were: (1) No

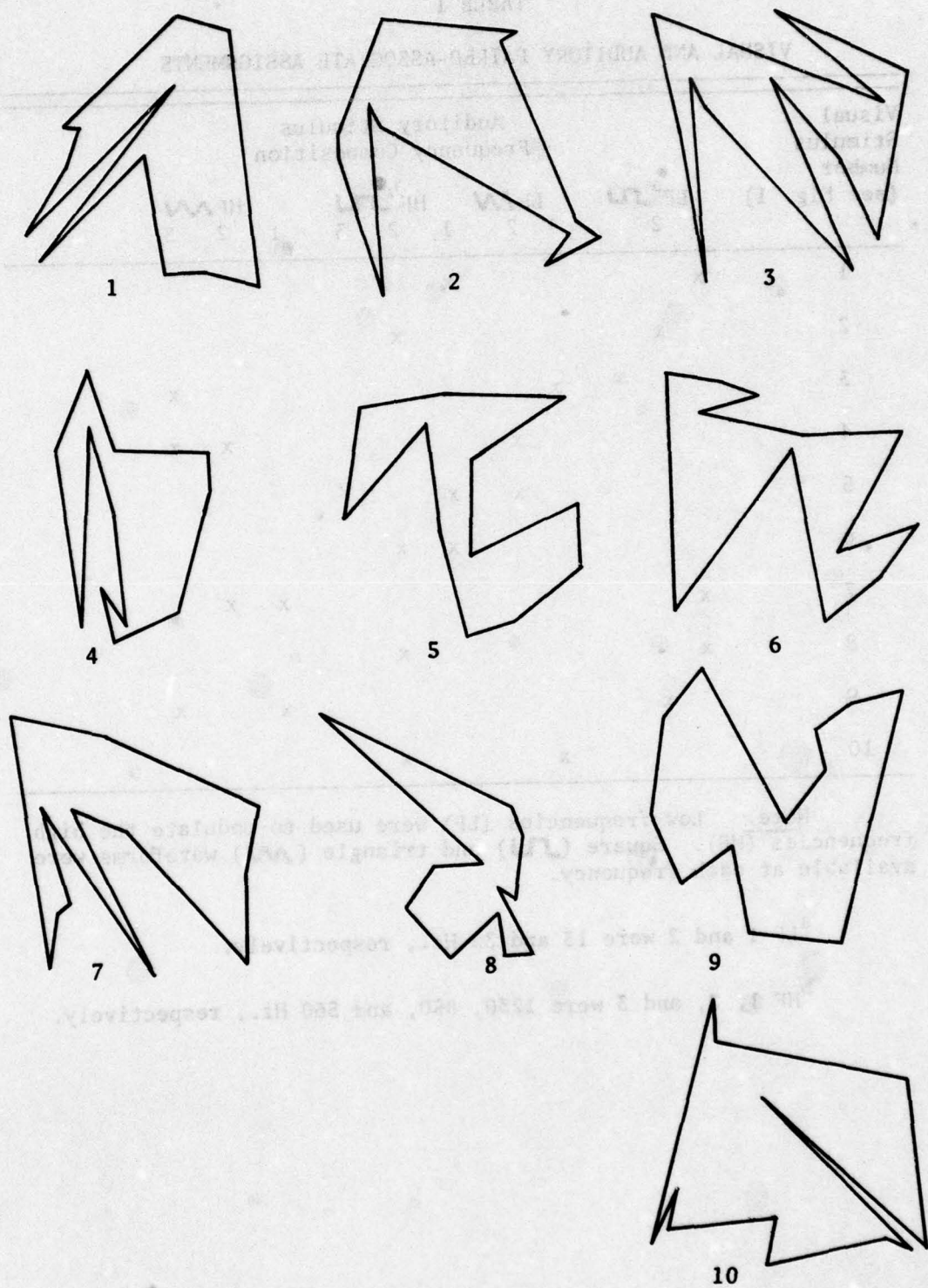








Figure 1. Visual stimuli.



TABLE 1

## VISUAL AND AUDITORY PAIRED-ASSOCIATE ASSIGNMENTS

Visual Stimulus Number (see Fig. 1)	Auditory Stimulus Frequency Composition									
	LF <sup>a</sup> 		LF 		HF <sup>b</sup> 			HF 		
	1	2	1	2	1	2	3	1	2	3
1	x				x					
2		x				x				
3			x						x	
4				x				x	x	
5				x	x					
6					x	x				
7	x							x	x	
8	x					x				
9		x						x		x
10			x			x				

Note. Low frequencies (LF) were used to modulate the high frequencies (HF). Square () and triangle () waveforms were available at each frequency.

<sup>a</sup>LF 1 and 2 were 13 and 33 Hz., respectively.

<sup>b</sup>HF 1, 2, and 3 were 1230, 850, and 560 Hz., respectively.

stimulus was repeated within a memory set; (2) The same probe was not used on adjacent trials; (3) On positive trials, each serial position was tested equally often; (4) Probability of a positive or negative probe was .5; (5) Half the probes were visual, half auditory (i.e., on any given trial there was a probability of .25 that the probe would be positive and visual, positive and auditory, negative and visual, or negative and auditory).

A completely within-subject design with repeated measures on all factors was utilized. The experiment was run under two conditions: modality irrelevant (MI) and modality relevant (MR).

Within the MI condition the positive set could be "pure" (all visual or all auditory) or mixed modalities. Pure memory sets were analyzed separately as a  $4 \times 2 \times 2 \times 2$  factorial (memory set size  $\times$  memory modality  $\times$  probe modality  $\times$  response type). A total of 20 replications per subject in each of the 32 cells was run.

Since it is impossible to have a mixed memory set with a single item, only sizes 2, 3, and 4 were used in this condition. The resulting design contained 12 cells: 3 (memory set)  $\times$  2 (probe modality)  $\times$  2 (response). The mixed memory set could be composed in several ways (a three-item set could be 2 auditory and 1 visual or 1 auditory and 2 visual; a four-item set could be split 3-1, 2-2, or 1-3). The frequency of each possible set composition was equal for each possible type of mixed set trial and the order in which auditory and visual probes occurred was random, subject to the constraints noted earlier. On positive trials in the MI portion



of the experiment there were an equal number of probe presentations in the same and opposite modality relative to its format in the memory set; i.e., the modality of the probe in the long run was irrelevant to the decision process.

The overall design of the MR condition was a  $4 \times 2 \times 2$  factorial (positive set size  $\times$  probe modality  $\times$  response). A special feature of the MR condition was the requirement that every positive probe must be in the same modality format as it appeared in the memory set. The number of items in the "relevant" modality was 1, 2, 3, or 4. The number of "irrelevant" modality items was varied so that all possible combinations of relevant and irrelevant items adding up to a total set of 1, 2, 3, or 4 resulted. Thus, if the number of "relevant" items was 1, the number of irrelevant items could be 0, 1, 2, or 3 for total sets of 1, 2, 3, or 4. If the number of relevant items was 2, the number of irrelevant items could be 0, 1, or 2, yielding sets of 2, 3, or 4. For each of the two relevant modalities, 10 types of memory sets resulted. Table 2 enumerates these combinations. Note that set size 4 occurs for 1, 2, 3, or 4 relevant stimuli, set size 3 for  $R = 1, 2$ , or 3, set size 2 for  $R = 1$  or 2, and set size 1 occurs only once ( $R = 1$ ). To control for an equal number of probes (20 in this experiment) for each number of relevant items, the number of trials per memory set size was varied: 40, 80, 120, and 160 trials for  $s = 1$  to 4, respectively. The order in which relevant and irrelevant items were presented within the memory set was randomized for each trial. Half

TABLE 2

## MEMORY SET COMPOSITION, MODALITY RELEVANT CONDITION

---



---

<u>s1:</u>	R
<u>s2:</u>	RR RI
<u>s3:</u>	RII RRI RRR
<u>s4:</u>	RIII RRII RRRI RRRR

---

Note. 50/50 Positive/negative response ratio throughout.

Note. R and I indicate relevant and irrelevant memory items, respectively.

of the trials terminated in negative probes, as in the MI condition. Appendix C shows the overall experimental design.

### Apparatus

Generation and display of visual stimuli, timing and control logic for visual and auditory stimuli, response recording and scoring, and most data analyses were performed by an IBM 370/155 computer coupled to an IBM 1827 Data Control Unit. Audio tones were generated by a specially-constructed multiple function generator unit designed by the author; a technical diagram of this device is available in Appendix A.

The subject was seated at an IBM 2250 Display Console in a sound-attenuated and darkened room. The visual stimuli subtended a visual angle of approximately 4.5 degrees at a distance of approximately 26 (10 cm.) inches from the cathode-ray tube display. Auditory stimuli were presented via headphones at a comfortable volume level. The headphones were worn at all times and the subject fixated at the location on the screen where the visual items would appear when they were presented. Responses were made by means of telegraph keys mounted 14 (5.5 cm.) inches apart on a panel inclined so that the subject could rest her arms and operate the keys with the finger tips. (See Figure 2.) Positive responses were assigned to the right hand, negative to the left. RT was measured to the nearest millisecond (msec.).

Except for operation of the manual start button, the experiment was controlled automatically through a special computer program developed by Brandt (1976).



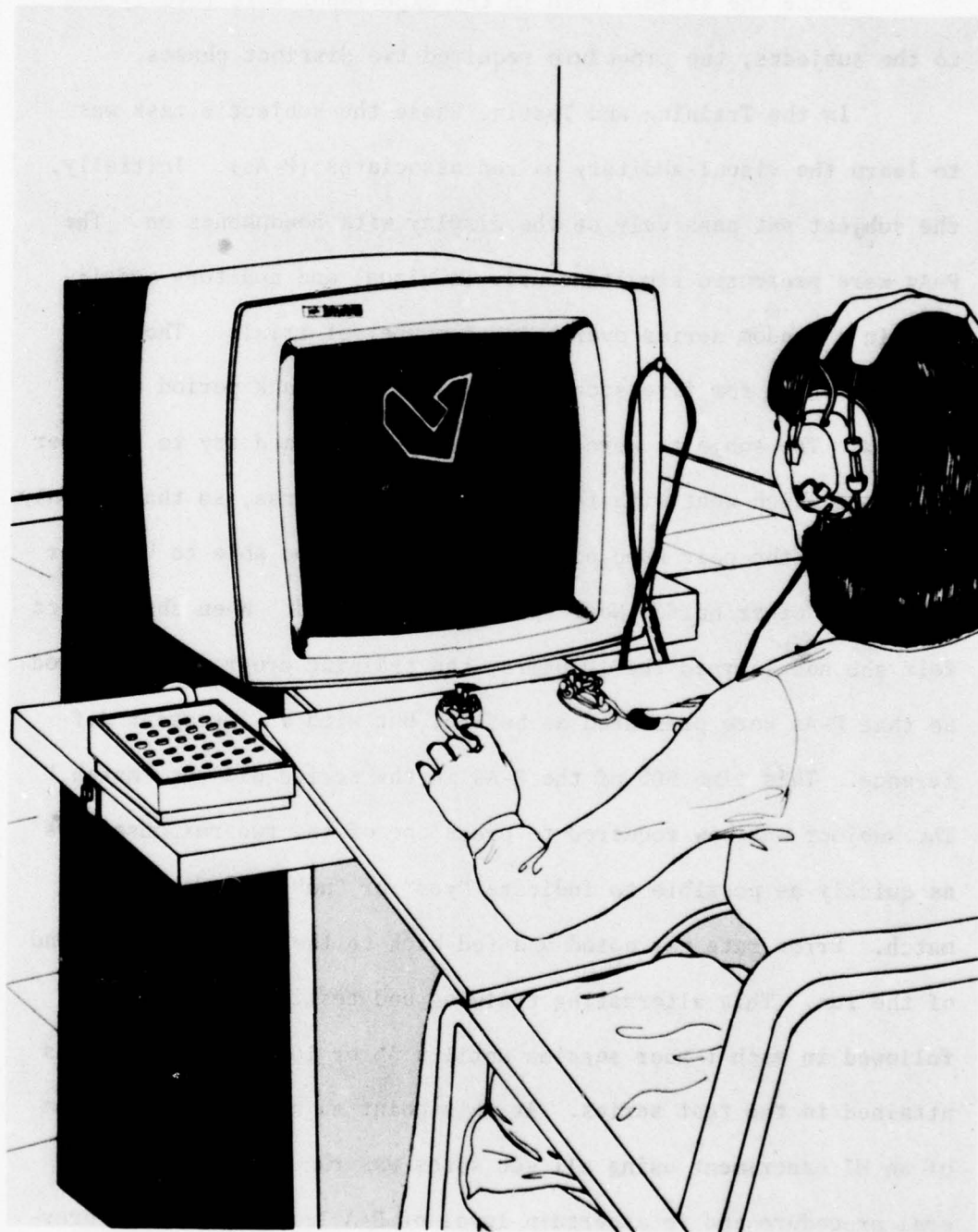


Figure 2. Subject at experimental console.

### Procedure

Since the stimuli used in the experiment were totally new to the subjects, the procedure required two distinct phases.

In the Training and Testing Phase the subject's task was to learn the visual-auditory paired associates (P-As). Initially, the subject sat passively at the display with headphones on. The P-As were presented simultaneously in visual and auditory modalities in a random series over a large number of trials. The pairs were presented for five seconds followed by a blank period of 2 seconds. The subjects were instructed to relax and try to remember the sound which went with the figure and vice-versa, so that if only one-half of the pair were presented they would be able to "see" or "hear" the other half. No response was required. When the subject felt she had learned the 10 pairs, the training program was altered so that P-As were presented as before, but with an important difference. This time 50% of the P-As in the series did not "match." The subject was now required to press one of the two response keys as quickly as possible to indicate "yes" or "no" regarding the match. Error rate was noted and fed back to the subject at the end of the run. This alternating training and testing routine was followed in each 1-hour session until a 5% or lower error rate was attained in the test series. At this point an abbreviated version of an MI experiment using all set sizes was run to establish general procedure and to ascertain level of P-A learning. If an overall error rate of greater than 5% was observed, the training/test procedure was repeated.

As anticipated, the P-A learning task was extremely difficult, even for highly motivated subjects; however, all subjects did successfully reach the P-A acquisition criterion. The Training and Testing Phase required from 20 to 40 hours per subject, extending over several weeks. The process could not be speeded up, due to competition with other users for the limited available computer time.

The Experiment Phase was begun immediately following the Training Phase. Every one-hour experimental session began with five minutes of practice with the memory set size about to be run. If the error rate on the practice run was excessive, a small "refresher" session was held prior to data collection.

Experimental runs were initiated by a subject-actuated start button. Ten seconds later one to four memory stimuli were presented sequentially for .75 sec. each with .25 sec. blank period between items. 1.25 sec. after termination of the last memory item a test probe appeared for 5 sec., or until the subject responded. A new trial began 3 sec. after the subject's response. Identical timings were used regardless of whether pure auditory (or visual) or mixed memory sets were presented; this was true for both the MR and MI conditions. As noted earlier, the only difference between MR and MI conditions, from the subject's point of view, was that positive probes in the MR condition would always be in the same format as they had appeared in the positive set. This fact was stressed in subject instructions (see Appendix B).



Burrows (1972) varied set size within a block of trials, so that one complete replication of all conditions occurred during that block. For the present study this approach was impractical for computer programming reasons. Instead, a block of trials consisted of a complete run within a specific set size and memory modality combination. Thus, in the MI condition subject #1, for example, received blocks of A3, V1, M3, A1, V3, M4, etc. (A, V, and M here denote auditory, visual, and mixed memory set presentation; set size is indicated by the digit following. This notation will be used for the balance of this paper.) Each of the remaining subjects, when in the MI condition, received her blocks of trials in a different sequence to balance for any order effects. In the MR condition, blocks of trials were based on set size alone. Each subject received a different random order presentation of the four set sizes. All data were collected for a single set size before proceeding to the next block; i.e., as in the MI condition, total set size was constant for a block of trials. However, the number of relevant stimuli in the MR condition could vary within a series of trials of a given set size, as shown in Table 2.

To counterbalance for the possibility of learning effects, half the subjects completed data collection under the MR condition first; then the MI condition was administered. The other half of the subjects participated in the reverse order.

Sessions were always one hour duration. The number of blocks of trials completed during the period varied according to two

factors: amount of practice required and the size of the memory load under test. All sessions began with a short practice period using the memory set size and format about to be used in the data collection. Since positive set presentation was sequential, a block of trials where  $s = 1$  took less total time than the same number of trials with  $s = 4$ .



### CHAPTER III

#### RESULTS

##### Reaction Time Analysis, MI Condition

Latencies for correct responses were used in calculating mean RTs for each subject at each of the levels of positive set size ( $s = 1$  to 4), memory modality (visual, auditory), probe modality (visual, auditory), and response (positive, negative)--a total of 32 cells. This constituted the data set for the "pure" memory set blocks. A separate analysis was performed for the mixed memory set blocks; memory set size (2 to 4), probe modality (visual, auditory), and response (yes, no) yielded 12 cells. Twenty scores per subject were collected for each cell in both the pure and mixed memory set presentations.

A four-factor analysis of variance on the pure positive set data yielded main effects for set size,  $F(3, 224) = 18.79$ ,  $p < .0001$ ; and response,  $F(1, 224) = 13.47$ ,  $p < .001$ . In addition, the memory modality x probe modality first order interaction was significant,  $F(1, 224) = 77.08$ ,  $p < .0001$ ; as was the second order interaction of these same two factors with set size,  $F(3, 224) = 2.59$ ,  $p < .05$ . No other main effects or interactions were significant. On the basis of the analysis, physical identity (A-A, V-V) scores were combined and a regression line for mean data plotted; associational identity (V-A, A-V) data were combined and plotted in a like

manner. The fitted regression lines accounted for 99% and 96% of the variance, respectively, in the positive response condition, with 97% and 90% fits obtained for negative probes. (See Figures 3 and 4.) The significant main effect of response indicated that, overall, positive probe RTs were 111 msec. faster than negative responses (positive grand  $M = 754$ , negative grand  $M = 865$ ).

In an additional analysis of the pure memory set data, least square regression lines were calculated for each subject in the positive response condition as a function of physical vs. associational matches. Student  $t$  tests for differences between means indicated that the intercepts were not different,  $t(7) = 1.82$ , n.s., but the associational and physical functions had different slopes,  $t(7) = 2.81$ ,  $p < .05$ . The same analysis performed on the negative data yielded similar conclusions: intercepts were not different,  $t(7) = 1.51$ , n.s., and different slopes,  $t(7) = 2.87$ ,  $p < .05$ . The conclusion is that the physical and associational match functions within Figures 3 and 4 have significantly different memory scan rates, but that the intercepts (probe encoding times) do not differ.

Since the data portrayed in Figures 3 and 4 appeared to depart from linearity, orthogonal comparisons were performed (Edwards, 1968; p. 145) to determine if there were higher order trends. In all four sets of data there was a highly significant linear trend ( $p < .01$ ), no significant departures from linearity, and no significant quadratic trends.



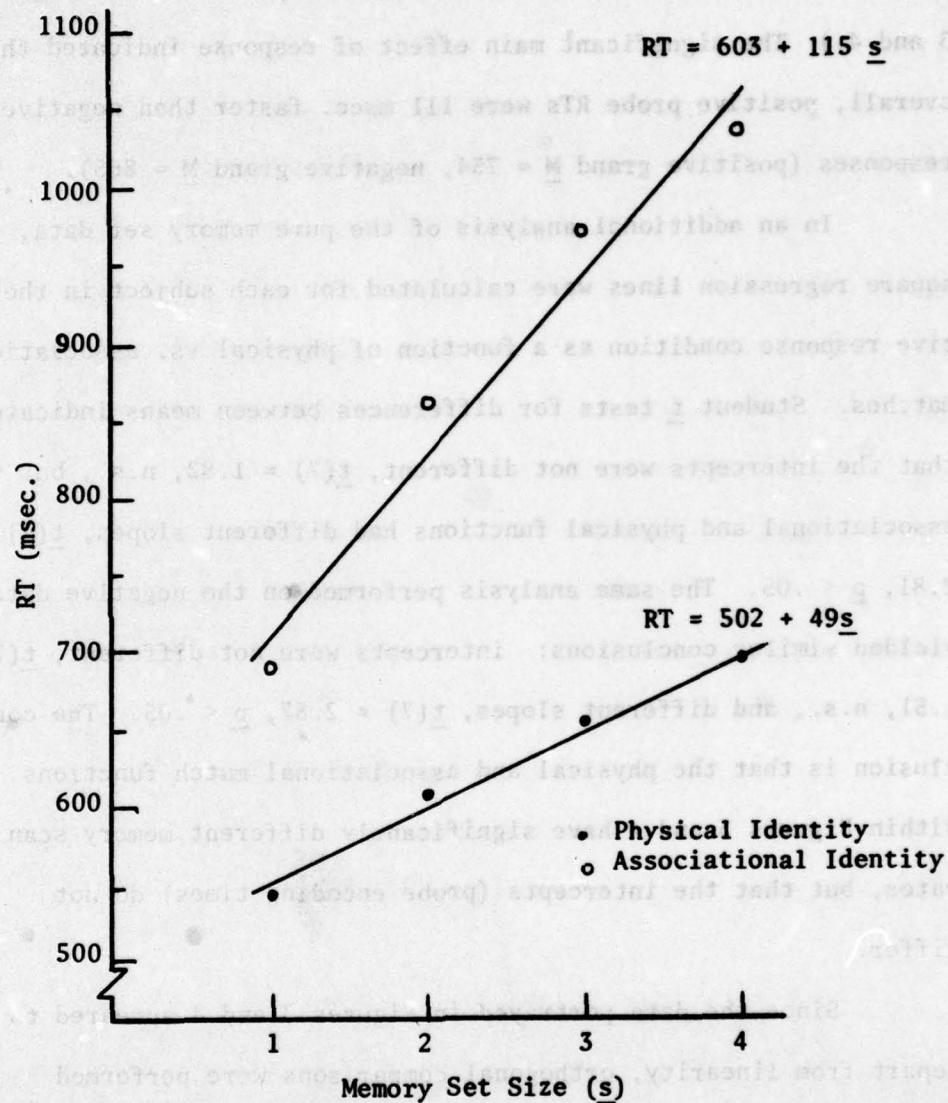


Figure 3. Reaction time as a function of physical vs. associational identity; positive responses.

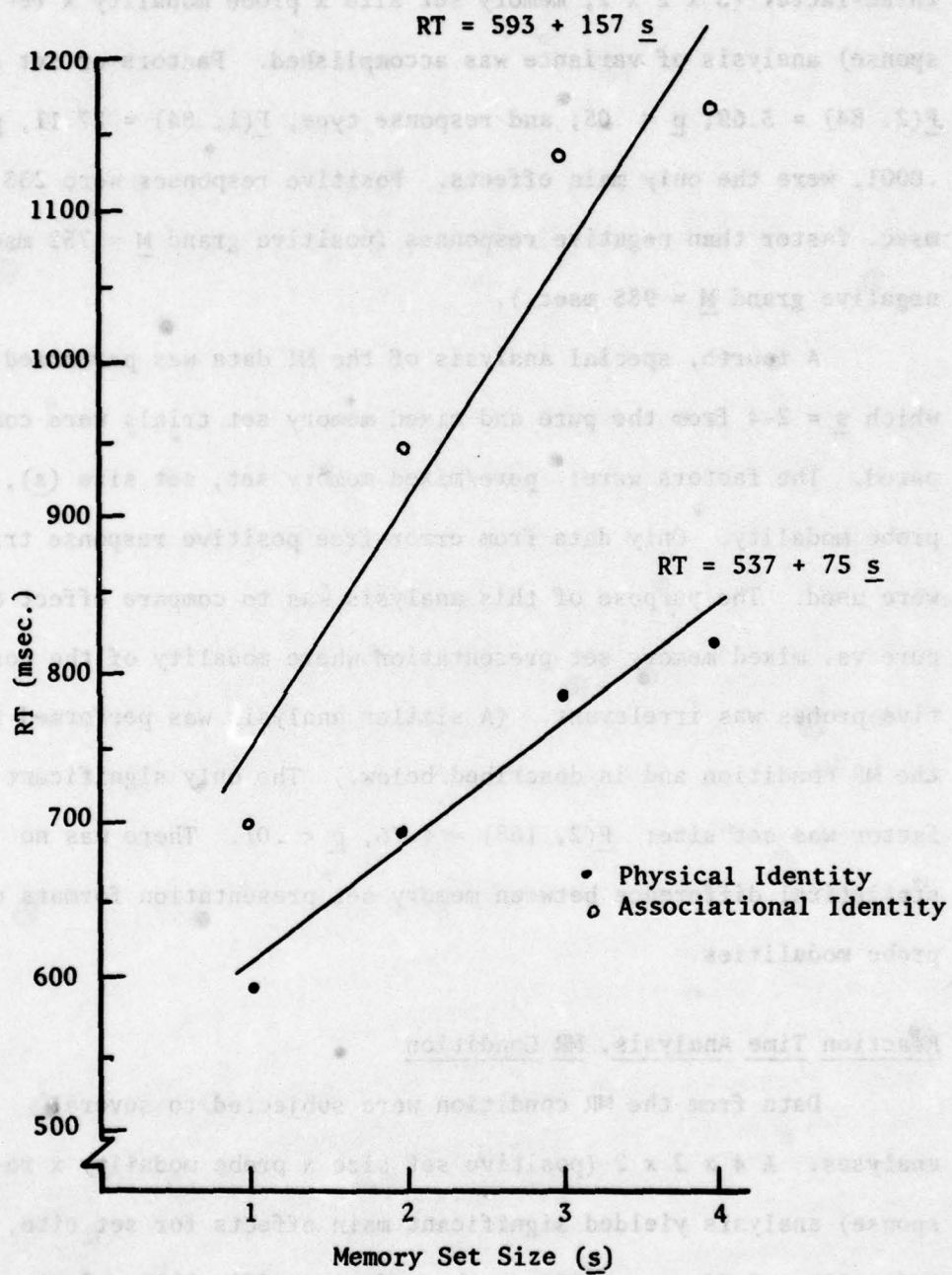


Figure 4. Reaction time as a function of physical vs. associational identity; negative responses



For the MI condition, mixed positive set blocks, a separate three-factor ( $3 \times 2 \times 2$ , memory set size  $\times$  probe modality  $\times$  response) analysis of variance was accomplished. Factors of set size,  $F(2, 84) = 3.69$ ,  $p < .05$ ; and response type,  $F(1, 84) = 27.11$ ,  $p < .0001$ , were the only main effects. Positive responses were 233 msec. faster than negative responses (positive grand  $M = 752$  msec., negative grand  $M = 985$  msec.).

A fourth, special analysis of the MI data was performed, in which  $s = 2-4$  from the pure and mixed memory set trials were compared. The factors were: pure/mixed memory set, set size ( $s$ ), and probe modality. Only data from error-free positive response trials were used. The purpose of this analysis was to compare effect of pure vs. mixed memory set presentation where modality of the positive probes was irrelevant. (A similar analysis was performed for the MR condition and is described below.) The only significant factor was set size:  $F(2, 168) = 4.76$ ,  $p < .01$ . There was no statistical difference between memory set presentation formats or probe modalities.

#### Reaction Time Analysis, MR Condition

Data from the MR condition were subjected to several analyses. A  $4 \times 2 \times 2$  (positive set size  $\times$  probe modality  $\times$  response) analysis yielded significant main effects for set size,  $F(3, 112) = 7.50$ ,  $p < .0001$ ; probe modality,  $F(1, 112) = 7.81$ ,  $p < .01$ ; and response type,  $F(1, 112) = 7.01$ ,  $p < .01$ . All interactions were nonsignificant. Auditory probes were faster than

visual by 76 msec. Positive responses were significantly faster than negative, with a 72 msec. difference. Table 3 summarizes this analysis. In order to study the effect of modality relevancy in the MR condition, that is, whether the subject could make use of the additional information, a 3 (set size) x 2 (probe modality) x 2 (pure/mixed memory sets) analysis was performed. Only error-free positive response data were used. All main factors were significant: memory set size,  $F(2, 84) = 5.42, p < .01$ ; probe modality,  $F(1, 84) = 9.92, p < .01$ ; and pure/mixed memory set,  $F(1, 84) = 4.99, p < .05$ . There were no significant interactions. As before, auditory probes were faster than visual and mixed memory sets were faster than pure sets. (See Table 4.) Since memory set sizes were the same for the pure and mixed portions of this analysis, the subjects apparently were able to use the modality information of the probe to limit the effective set size and thus speed their responses in the mixed memory sets--something they were not able to do under the MI condition.

#### Reaction Time Analysis, Between MI and MR Conditions

Due to the experimental design, comparisons between the major experimental conditions were possible; as noted earlier, Burrows (1972) was unable to conduct such analyses. Two ANOVAs were performed; both utilized correct positive response data. In the first, pure memory set physical identity data from the two conditions were studied in a 4 x 2 x 2 design. Factors were set size (1 to 4), experimental conditions (MI and MR), and memory/probe



TABLE 3

MEAN RT TO AUDITORY AND VISUAL PROBES AS A FUNCTION OF  
RESPONSE TYPE, MR CONDITION ( $s = 1$  to 4)

Response Type		Probe Modality		$\bar{X}$
		Visual	Auditory	
	Positive	600	535	567
	Negative	682	596	639
	$\bar{X}$	641	565	

TABLE 4

MEAN RT TO AUDITORY AND VISUAL PROBES AS A FUNCTION OF  
PURE VS. MIXED MODALITY MEMORY SETS, MR CONDITION  
( $s = 2$  to 4)

Memory Set Probe		Probe Modality		$\bar{X}$
		Visual	Auditory	
	Pure	676	575	626
	Mixed	600	532	566
	$\bar{X}$	638	553	



modalities (V and A). Significant main effects were noted for set size,  $F(3, 112) = 11.97$ ,  $p < .0001$ ; and memory/probe modality,  $F(1, 112) = 12.43$ ,  $p < .001$ . No interactions were significant. It is important to note that the MI-MR manipulation made no difference,  $F(1, 112) = 2.20$ ,  $p < .14$ . Such a finding would be expected, since modality information presumably would not be of value for positive probes in the pure conditions. However, the second analysis compared data from the two conditions where the memory set was mixed. The resulting  $3 \times 2 \times 2$  design (memory set size  $\times$  MI/MR  $\times$  memory/probe modality) yielded significant main effects for all three factors: set size,  $F(2, 84) = 4.08$ ,  $p < .05$ ; experimental condition,  $F(1, 84) = 8.61$ ,  $p < .01$ ; and modality,  $F(1, 84) = 7.05$ ,  $p < .01$ . All interactions were nonsignificant. When memory sets were mixed, knowledge of modality was useful in speeding the decision; overall, the MR pure memory set condition was 70 msec. faster than the MI pure condition. In addition, auditory probes were responded to 64 msec. faster than visual probes, on the average. Table 5 summarizes these data.

#### Error Analysis

Error scores were recorded for all conditions and are shown as percent relative error in Table 6. Overall, the error rate was 12.2% for MI, 4.7% for MR conditions. Compared to other Sternberg studies the MI rate is high; typically, errors occur in the 2 to 8% range elsewhere. However, when compared with Burrows' (1972) Experiments 1 and 2, which correspond to the MI and MR

TABLE 5

MEAN RT TO AUDITORY AND VISUAL TEST PROBES AS A FUNCTION OF  
MODALITY IRRELEVANT (MI) VS. MODALITY RELEVANT (MR)  
CONDITION, MIXED MEMORY SETS  
( $s = 2$  to 4)

Condition		Probe Modality		$\bar{X}$
		Visual	Auditory	
Condition	MI	758	744	751
	MR	603	536	570
	$\bar{X}$	681	640	

TABLE 6

## ERROR ANALYSIS

Modality Irrelevant Condition		Modality Relevant Condition	
<u>Pure Sets</u>		<u>Mixed Sets</u>	
Probe: A = 11.9, V = 12.1 Pos. = 14.2, Neg. = 9.8		Probe: A = 13.0, V = 13.3 Pos. = 16.6, Neg. = 10.8	
Match: Physical = 5.4 Associational = 18.6		Probe: A = 4.0, V = 5.4 Pos. = 6.8, Neg. = 2.7	
<u>s1</u> = 6.1 <u>s2</u> = 8.3 <u>s3</u> = 16.5 <u>s4</u> = 17.1 Grand Mean = 11.2		<u>s2</u> = 3.0 <u>s3</u> = 4.7 <u>s4</u> = 9.5 Grand Mean = 4.7	
<u>Overall</u>		<u>Overall</u>	
Probe: A = 12.5, V = 12.7 Pos. = 15.4, Neg. = 10.3 Grand Mean = 12.2			



conditions in the present study, the 12.2% and 4.7% rates occur in about the same ratio as his 10% and 4% errors, respectively. The data merely provide further evidence for the high difficulty level of the MI task.

In general, those portions of the experiment which yielded high error rates also produced longer RTs. Other findings are also in line with expectations: errors increased monotonically as a function of set size; associational match error rates were higher (roughly three times) than those for physical matches; positive responses were 50% more error-prone than negative responses. The positive covariation between error rate and RT indicates that the observed effects are not simply due to a speed-accuracy tradeoff. Wickelgren (1977) has criticized investigators doing RT experiments for failing to take into account the speed-accuracy tradeoff. He has acknowledged, however, that ". . . When both errors and reaction times go in the 'same' direction, then it is reasonably safe to conclude that the condition which is slower and has more errors is more difficult than the condition that is faster and has fewer errors" (p. 79). Note also that auditory and visual probes had virtually identical error rates in all conditions; apparently probe modality had little effect on accuracy in stimulus discrimination ability.

#### Serial Position (SP) Analysis

A 2 x 2 x 3 analysis of variance was performed on the correct positive RT data from pure memory set size 4 in the MI condition. Factors were memory modality (2), probe modality (2), and

serial position of probe (3). Due to an error in developing the stimulus sequences, no data were collected for the A-A combination at serial position 1. Therefore, only SP2 through 4 were included in the statistical analysis. Significant main effects were found for memory set modality,  $F(1, 84) = 4.52, p < .05$ ; and serial position,  $F(2, 84) = 7.95, p < .001$ . Probe modality was not significant. Figure 5 portrays these findings. (For information purposes, mean values from the available SP1 data are plotted. The only other significant effect was the expected interaction between memory and probe modalities,  $F(1, 84) = 43.16, p < .0001$ ; i.e., physical matches were faster [grand  $M = 673$  msec.] than associational matches [grand  $M = 1003$ ].)

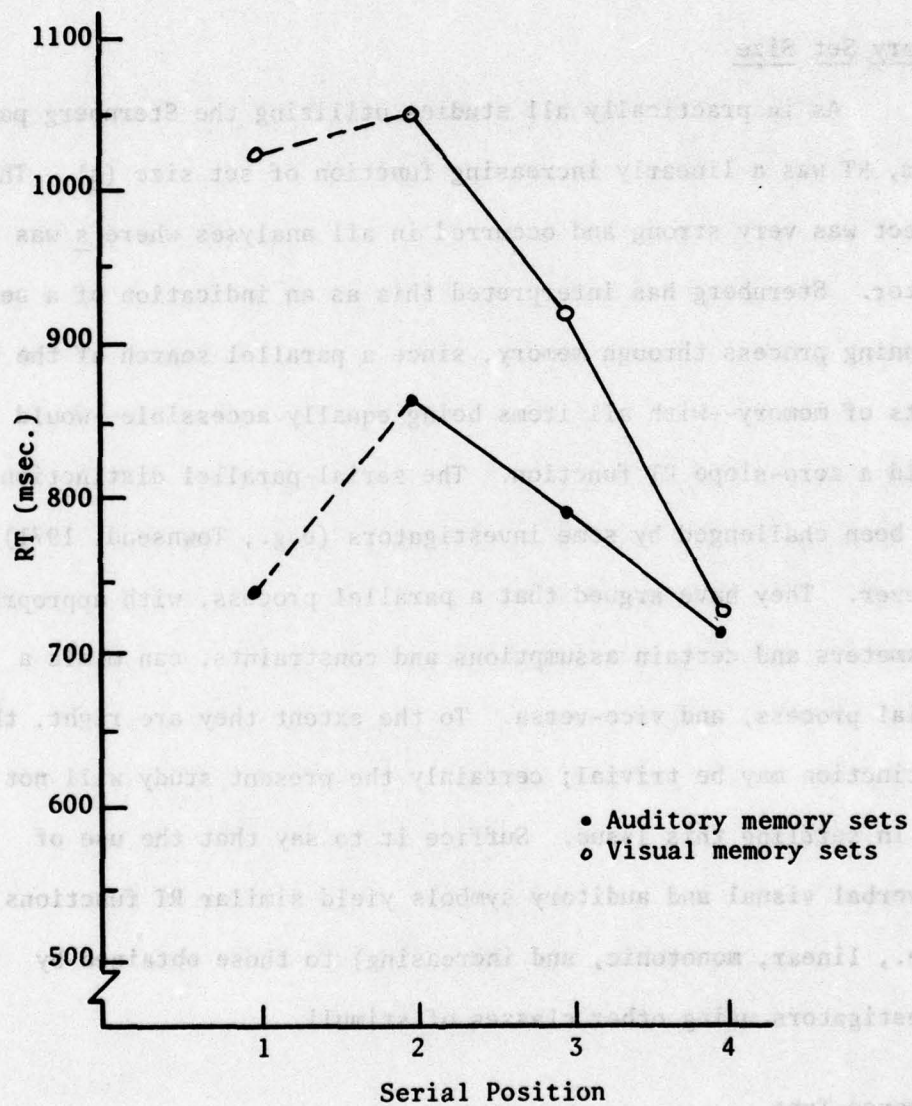


Figure 5. Reaction time as a function of serial position for  $s = 4$ , pure memory sets, MI condition. (Serial position 1 data are incomplete.)



## CHAPTER IV

### DISCUSSION

#### Memory Set Size

As in practically all studies utilizing the Sternberg paradigm, RT was a linearly increasing function of set size ( $s$ ). This effect was very strong and occurred in all analyses where  $s$  was a factor. Sternberg has interpreted this as an indication of a serial scanning process through memory, since a parallel search of the contents of memory--with all items being equally accessible--would yield a zero-slope RT function. The serial-parallel distinction has been challenged by some investigators (e.g., Townsend, 1971), however. They have argued that a parallel process, with appropriate parameters and certain assumptions and constraints, can mimic a serial process, and vice-versa. To the extent they are right, the distinction may be trivial; certainly the present study will not aid in settling this issue. Suffice it to say that the use of nonverbal visual and auditory symbols yield similar RT functions (i.e., linear, monotonic, and increasing) to those obtained by investigators using other classes of stimuli.

#### Response Type

Another strong effect, not obtained by all investigators, was the influence of positive versus negative probes on overall RT. In all conditions, positive was faster than negative. Further, the

RT differences were evidenced in the intercept of the function; i.e., there were no instances where probe type interacted with set size. Under the terms of the prevailing interpretations of such data, the scan through STM was exhaustive rather than self-terminating. A self-terminating search would have yielded positive RT slopes one-half the value of those for negative probes. Other investigators--most notably Theios and his associates (e.g., Theios, Smith, Haviland, Traupmann, and Moy, 1973)--have produced evidence for a serial self-terminating search. But this is observed more often under the fixed-set procedure method of presentation; the present study used a varied-set procedure, in which positive (and negative) sets changed every trial.

It is interesting to compare positive and negative response differences between the experimental conditions. The MI condition required 185 msec. longer overall for negative than for positive responses. For the MR condition, the difference dropped to 72 msec. (All differences were significant.) This 2.5X reduction in difference between response types can be considered as additional evidence that subjects can use modality information in their memory search. Recall that subjects serving in the MR condition knew that they only had to scan memory items which were in the same format (relevant modality) as the just-presented probe. Recall also that the number of items in the relevant modality could vary from zero to the full memory set (s). In the long run, then, subjects, if they were able to utilize the modality information, would only have to



scan a maximum of two items in the MR condition. The failure of probes in the MI condition to provide any such modality information for assisting in memory scan would require that the subject scan all memory items (maximum of 4). In addition, the MI mixed trials required some additional processing of the probe and/or memory set when the first scan of memory produced a "no-match" output. This was likely due to the fact that the subject could not be sure the positive memory item was not in the opposite modality, if indeed there was a positive item in the memory set. All this stimulus "manipulation" in the MI condition resulted in substantially longer positive-negative RT differences (and increased errors) compared to the MR, even though actual memory set sizes were the same in both cases.

#### Serial Position

Analysis of the serial position (SP) data provides additional (though problematical) information regarding the scanning process. (See Figure 5.) Serial position of the probe produced a strong recency effect on RT. Interestingly, probe modality made no difference. However, memory modality exerted a strong influence in the earlier serial positions, decreasing to no difference at SP4. The exhaustive search model as proposed by Sternberg predicts a flat SP curve (i.e., no SP main effect), since all positions would be scanned every trial. The strong SP effect observed in the present study would appear to eliminate an exhaustive scan interpretation. Note that this conflicts with the parallel positive and



negative RT slopes--cited earlier as evidence for an exhaustive scan. On the other hand, the process does not appear to be fully self-terminating either. Although not included in the ANOVA (due to one empty cell), the available mean data from SP1 have been plotted in Figure 5. The points shown include data from three out of four memory/probe combinations, and so are reasonably representative of the values one would expect with the complete data set. At the very least, the SP1 data provide an indication that the linear monotonic (increasing or decreasing) functions required by the self-terminating model are not present.

Burrows and Okada (1971) have proposed a serial-exhaustive scan model which can accommodate results such as those observed here. The model is based on two assumptions: (1) a memory item can be in a High (H) or Low (L) "accessibility" state, and (2) time for a positive item match is shorter than for a mismatch when the item is in state H. (Times are equal in state L.) Presumably, material is placed in state H whenever it is "structured" in some way. For example, items occurring at the beginning or end of list would be in state H due to their being at a "boundary" location, and, therefore, would be responded to faster than items in the middle of the list. "Structure" could also be imposed by presenting some memory items more than once or at a greater intensity than others. Burrows and Okada admit it is possible to construct alternative models which make similar predictions and that more detailed development of their model is required. The present study, unfortunately, can offer no additional assistance in this area.

Returning to the memory modality effect in the SP analysis, the present data appear to reflect the differential decay rate of visual and auditory sensory memory traces--Neisser's (1967) "iconic" and "echoic" memories, respectively. Recall that the memory items in the present experiment were presented sequentially at one-second intervals. An item in SP1, then, had to be retained 3 sec. longer than an item in SP4. Also, data indicate a significantly longer RT for visual items occurring in the early SPs, with the effect disappearing at SP4. Although not a major objective of the experiment, the results do provide further evidence for a differential loss of availability of STM information as a function of presentation sensory modality.

#### Translation Effect

An increase in RT for associational matches over physical matches, the translation effect, was obtained. As Figures 3 and 4 show, there was a significant increase in slope when a translation (associational match) was required; and similar effects were noted for both positive and negative response data. However, unlike the results of some other investigators (e.g., Swanson et al., 1972; Chase and Calfee, 1969), intercepts did not differ significantly. It was hypothesized earlier that the increase in Stage 1 (intercept) time recorded by Chase and Calfee (1969) and Swanson et al. (1972)--in addition to a slope increase--might be due to differences in "verbal codability" of the stimuli used. The 16-sided random polygons used by Swanson et al. were paired with two-digit numbers.



It seems reasonable that with these stimulus materials, all visually presented, the digits, having their own overlearned verbal labels, would be more quickly encoded than the random figures whose "names" had just been assigned by the experimenter at the beginning of the study. (This is assuming, of course, that the "name" of the probe is necessary for the subsequent memory scan process. The case will be made shortly for a process which does not necessarily require such a transformation.) Similarly, in the Chase and Calfee study the superiority of auditory over visual probes, in terms of lower intercepts, could be explained by the experimenter's use of letters, which all have well-learned names. (A "name" can be defined as an auditory/articulatory label for an entity.) In both studies, the physical identity functions had parallel slopes; only the intercepts, as a function of the format of the probe, were different.

Cruse and Clifton (1973) used letter-digit pairs in their investigation of the translation effect. They found no intercept differences, but did obtain the usual slope effect. In terms of ease of verbal coding, both letter and digits possess readily available names, so that, if the hypothesis were true, the similar Stage 1 processing times as a function of probe format would have been predicted.

One of the purposes of the present study, then, was to develop stimulus pairs in which neither element had an advantage, from a verbal coding point of view, but which would also provide



the ability to study memory coding and scanning processes across two sensory modalities. The attempt appears to have been successful. RTs to auditory probes were not significantly different from visual probes overall, nor were their RT function intercepts different.

Positive probes which occurred in the opposite modality added an average of 66 msec. processing time per memory set item. For negative probes, the translation process added 82 msec./item. The results are similar to those of Cruse and Clifton (1973) and Swanson et al. (1972); both groups interpreted the translation effect as a "list translation." That is, when a probe is presented which differs in format from the memory set, the subject serially translates each memory item into the format of the probe. A "probe translation" model would have been indicated if slopes were similar, but with an intercept difference.

It must be remembered that the translation effect analysis comes from pure memory set data in the MI condition. When the memory set is mixed and the modality of the probe is relevant (MR condition), there are differences in RT as a function of probe modality. The list translation hypothesis cannot account for these differences; therefore, an alternative hypothesis will be proposed in the next section.

#### Modality-Specific Encoding

The primary purpose of this research was to examine encoding processes as a function of sensory modality, in the manner of

Burrows (1972). Through the creation of nonverbal auditory-visual paired-associates, it was felt that a bias toward auditory/articulatory encoding of commonly-used verbal stimuli could be reduced. With this bias minimized, one could then create a situation in which maintenance of the original sensory information (the MR condition) would be an advantage, if this information were available. If not, then there would be no performance differences between the MR and MI condition, in which sensory information was irrelevant.

Support for a multiple code generation process comes from data indicating that the subjects could use modality information to control their search through memory; overall, RTs were significantly faster in the MR mixed memory set than in the MI mixed condition, with similar memory set sizes and compositions. Apparently, it was useful to know that positive probe modality in the MR condition would always be in the same format as its presentation in the memory set. Positive probes in the MI condition, however, could also occur in the opposite modality; probe modality information was of no value in speeding the memory search in these instances.

An analysis comparing the MI vs. MR pure memory set conditions yielded no difference. This was not unexpected, since on positive probe trials knowledge of the modality would yield no information which could give a subject serving in the MR condition an advantage. There would be no functional reduction in memory set size. In addition, analyses within the MI and MR conditions--



comparing pure vs. mixed memory sets--showed that mixed set RTs in the MR condition were 61 msec. faster overall (Table 4) than pure sets of equal s-value, while no difference was noted for a similar comparison in the MI condition.

In comparison, results from Burrows' Experiment 1, similar to the MI condition here, showed a superiority for auditory probes when the memory set was all auditory; no advantage in the other combinations, including mixed memory sets. He found the same effect in Experiment 2 (analogous to the present MR condition); that is, an auditory probe following an all-relevant auditory memory set was faster than any other memory/probe combination. Furthermore, he found the mixed memory set RTs (regardless of probe modality) to be virtually identical to the all-relevant visual memory data. The MR condition in the present investigation yielded significantly faster RT for mixed than for either all-visual or all-auditory relevant memory sets. The mixed set superiority main effect was just as strong for visual (if not stronger) as it was for auditory probes. It is clear that subjects in this study could maintain visual information for use in a subsequent memory scan.

Burrows also analyzed his MR data in terms of the number of relevant items (R) as the memory set size was held constant at s = 4. Increases in RT as a function of R, he noted, would provide strong evidence for the subject's ability to store visual and auditory information separately. He failed to find any differences whatsoever, except that, overall, auditory probes were faster than visual.



A similar post hoc analysis was done on the MR correct positive response data for  $\underline{s} = 4$  in the present study. Factors were probe modality (A and V) and number of relevant items ( $R = 1$  to 4). As with Burrows, the auditory probes provided faster responses,  $F(1, 56) = 10.35$ ,  $p < .01$ , but  $R$  just failed to have an effect overall,  $F(3, 56) = 2.40$ ,  $p = .07$ . To further study the effect, separate Newman-Keul tests for pairwise differences between means for the auditory and visual probes was performed. The means are shown in Table 7. The only statistical significant difference was between  $R = 1$  and  $R = 4$  for the visual probes ( $p < .05$ ). However, a clear trend is evident in the data, which is totally absent in Burrows results--that is, the orderly, monotonic changes in RT as a function of  $R$ . His data varied almost randomly about the means and through a narrow range (58 and 26 msec. for auditory and visual, respectively). Once again, the present data provide evidence that the subject can reduce the effective set size on the basis of modality information.

The significantly faster auditory probe effect in the MR condition was subjected to closer scrutiny. The overall ANOVA did not explain where in the binary choice process the auditory probes were enhancing performance. Therefore, least square regression lines were developed for each subject in the MR condition, then mean slope and intercept parameters across subjects were calculated. A t-test for differences in correlated means was performed on these two parameters for auditory (A) and visual (V) probes, positive

TABLE 7

MEAN RT TO AUDITORY AND VISUAL TEST ITEMS AS A FUNCTION OF  
NUMBER OF ITEMS PRESENTED IN THE RELEVANT MODALITY,  
MR CONDITION ( $s = 4$ )

Modality of Test Item	Number of Items in Relevant Modality	Mean RT (msec.)
Auditory	4	619
	3	565
	2	552
	1	543
Visual	4	786
	3	745
	2	650
	1	592

response data. The analysis showed that the slopes of the A and V probe functions differed significantly,  $F(7) = 3.76$ ,  $p < .01$ , but intercepts did not differ,  $t(7) = -.92$ , n.s. The functions are shown in Figure 6. Trend analysis of these data showed significant linear trends, but no significant departures from linearity nor significant quadratic components. The 37 msec. per item scan rate for auditory probes was the fastest of all experimental conditions, and was just half the MR visual probe scan rate (75 msec./item). The memory scanning stage, then, appears to be the locus of the significant main effect superiority of auditory over visual probes in the MR condition. Failure to find any RT intercept differences indicates that the effect cannot be attributed to differences in encoding times.

A remaining question, of course, is why auditory scans were faster when probe modality was relevant (MR) than when it was not (MI). This can be subsumed under a more general question, namely, what hypothetical memory encoding/scanning process can capture the MR auditory superiority effect, as well as the translation effect noted earlier in the MI data? Posner (1973), in a review of experiment conducted by himself and other investigators, concludes that any model of memory coding and scanning must first of all include a process whereby multiple codes of the memory items are generated at the time of memory set presentation. That is, when a visual memory item is presented, for example, its auditory counterpart is generated simultaneously, or vice-versa. The stored representations



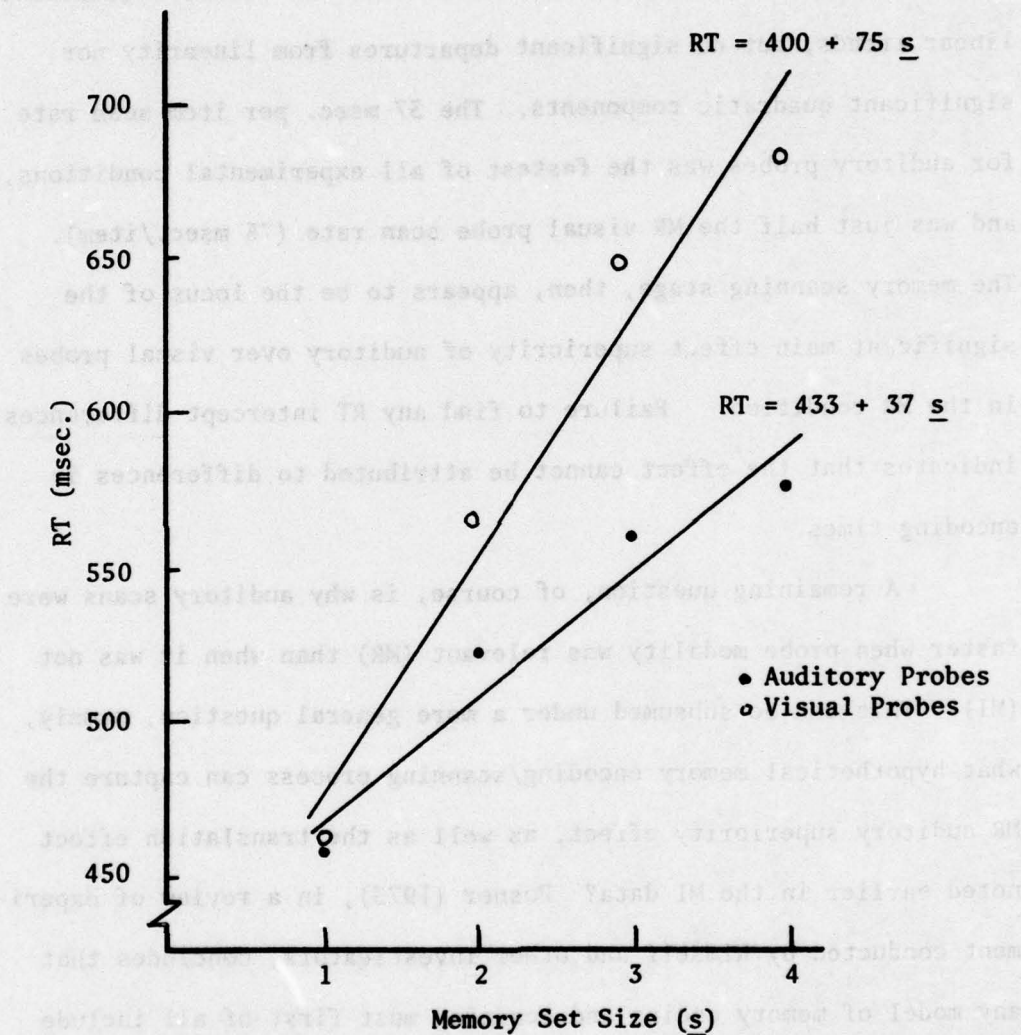


Figure 6. Reaction time as a function of probe modality; MR condition, positive responses.

would differ in strength, with the generated versions being weaker. Posner further hypothesizes that scan rates vary as a function of memory strength; i.e., it would take more time per item to scan the memory set on a V-A trial (where the weaker generated auditory versions of the visual items would be compared to the auditory probe) than for an A-A trial (where the stronger primary modality memory set is being scanned). Also, in this model subjects tend to bias their rehearsal efforts toward one code over the other. The code chosen for rehearsal is based on task configuration. An example would be the bias caused by subject expectations, as observed in the Tversky (1969) study using unequal probe probabilities. In equal-probability situations the rehearsal strategy is more uncertain. Posner notes that the direction of the bias would probably be determined by "...habits and preferences which reflect a particular culture's or individual's learned experiences" (p. 53).

Clifton, Sorce, and Cruse (1977) in recent series of experiments have arrived at the same conclusion as Posner. (Curiously, they make no reference whatsoever to Posner's earlier work.) They state that "...the apparent speed with which memory is searched decreases when translation, or recording, is required between presented items and a probe item, whether the translation scheme involves letters and digits, arbitrarily paired words of different classes, or well-known names. The translation effect, however, does not arise because of translation operations performed after the probe is presented. Rather, the necessary translations are done

when the to-be-remembered items are presented or rehearsed" (p.23).

A scenario can be proposed for the present study, then, which incorporates the previous hypothesis, as well as conclusions reached earlier in this discussion:

(1) In all conditions, a same-modality stimulus representation and its opposite modality associate are simultaneously generated as the memory set items are presented, the primary modality representations being higher in strength.

(2) Memory items are "rehearsed" (maintained). In the MI condition the subject has no foreknowledge whether the probe will match the memory set modality; there is therefore no reason to bias the rehearsal toward a particular modality. Under the MR conditions, the subject knows that a translation will never be required; thus there is a requirement to rehearse only the primary, same-modality representation.

(3) After the probe has been presented it is encoded and compared serially and exhaustively with each of the memory items. The time per comparison is an inverse function of the individual item trace strength. In the MI condition, pure physical matches are most rapid, since the comparison is based on the stronger same-modality representation. The MI pure associational matches are slower due to the requirement for comparing the probe against the weaker associative representations. The MI mixed memory set matches are slowest of all since the probe must first be compared to the same-mode items, then a rescan at the slower rate occurs for the



items requiring translation. (Alternatively, the scan process might consider each item in turn, accelerating and decelerating as a function of same vs. different modality. More intensive study into the mixed memory set technique should be pursued.) Scanning in the MR condition is fastest of all, since the maximum number of items to be scanned has been reduced, and scanning the weaker associative representations is never required. Further, subjects appear to bias rehearsal in favor of the auditory items, since they were scanned significantly faster than visual. (Part of this effect might be explained by the slower decay rate of auditory information, as shown by the serial position analysis. Recall, though, that the SP data came from the MI pure condition; it is therefore somewhat risky to apply these findings to the MR condition.) It is not apparent whether preferred rehearsal of the auditory items is due to "habits which reflect the individual's learned experiences," as Posner conjectured, or to some other as-yet-unknown process. Closer examination of this effect should be made.

(4) On the basis of the scan a "match" or "no-match" decision is made. This is decoded and a response ("right-hand" or "left-hand") chosen, and executed. Data from the present study indicate that more time is required for decoding a "no-match" response, the amount dependent upon whether MI or MR condition was in effect. This additional time has been noted by Sternberg (1975) and other investigators.

## CHAPTER V

### SUMMARY AND CONCLUSIONS

#### Summary and Conclusions

The present study was conducted to provide a new methodology for investigating memory encoding and scanning processes as a function of sensory input modality. Unique, nonverbal visual/auditory stimulus paired associates (PAs) were learned by the subjects. These PAs were then used in a Sternberg paradigm-based set of experimental conditions. In one condition the memory set was all one modality (pure) or mixed-modality. The probe might occur in either mode, and, if it matched one of the memory items, might be either physically the same or the associate of the matched item. This was called the Modality Irrelevant (MI) condition. In the Modality Relevant (MR) condition similar memory sets were used but the probe, if a match was present, was always in the same format (modality) as its occurrence in the memory set. That is, the subject never had to consider the associate form of the probe. In both conditions negative, no-match probes were also presented.

The use of nonverbal visual, and especially, auditory nonverbal stimuli was intended to provide a different way to examine the single vs. multiple memory code issue. Evidence for both types of memorial representation have been presented in the literature. It was this investigator's opinion that the single code (usually characterized as the auditory/articulatory "name") proponents had based



their interpretation on the use of verbal materials, or pictorial materials with well-learned common names. Under such circumstances, the storage of a single name code would be a good strategy. But what if the information was more abstract--if it did not have a readily available "name?" Perhaps the coding process was under the control of the subject, consciously or unconsciously, to the extent that he could store stimuli in a manner which would preserve information relative to its modality (format). Given the right circumstances, it might be a more efficient strategy to store a multiple code of each memory item and assess the information directly rather than through some single intervening representation.

The results of the present study indicate that the subject is able to utilize modality-specific properties of the stored memory items. This was observed in the significantly faster RTs for MR than MI probes, using identical memory set compositions in both cases. Further evidence came from within the MR data, where faster RTs were observed for mixed memory than for pure memory sets; there was no difference in a similar MI analysis.

In general, the results support Sternberg's position--namely that memory scanning in short-term memory is a serial exhaustive process. The increasing, monotonic, parallel positive and negative RTs as a function of memory set size was cited as evidence for this conclusion. A serial position (SP) effect was noted, which did conflict with Sternberg's model; SP curves should be flat, he noted. One possible explanation for the present SP data--while still



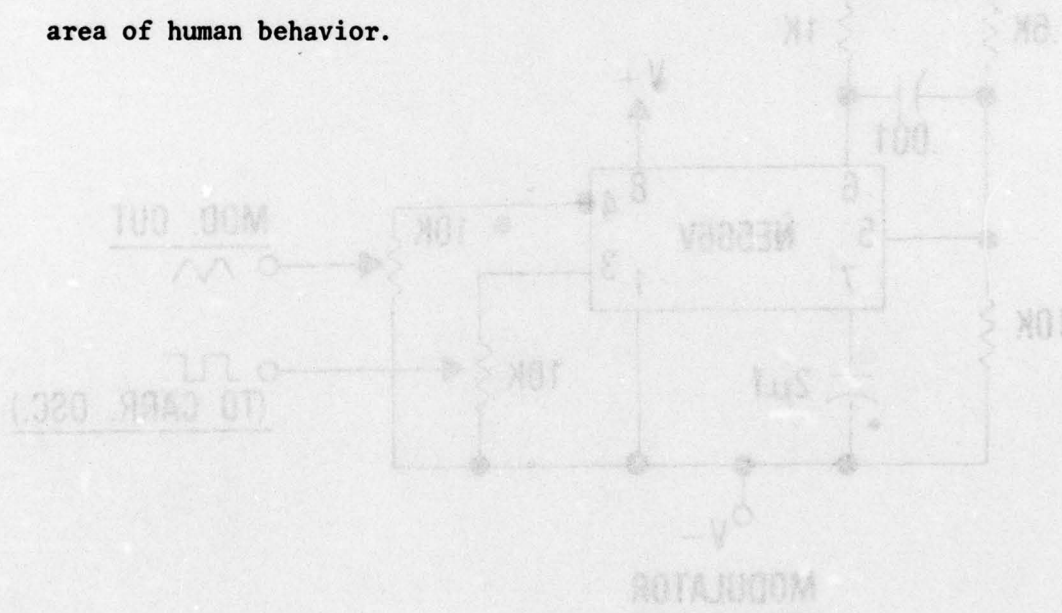
maintaining the exhaustive scan process--was suggested. It was based on the assumption of unequal memory strengths of the stored items, the relative strengths being determined by the "structure" of the memory set. Items at a boundary, for example, would be stronger.

A "translation effect" was observed. That is, positive probes which were in the same modality were significantly faster than positive probes which were associates (cross-modality). The effect was obtained for both auditory and visual probes. The translation effect was due to a slower scan rate (more time per item) for associate probes. A "list translation" interpretation--in which every item in memory is translated to its associate form following the presentation of an opposite modality probe--was discarded, due to significant probe modality differences in the MR condition. This effect was traced to faster scan rates for auditory probes. The list translation hypothesis does not accomodate such differences.

It has been proposed that a multiple code is generated at the time the memory set is presented, as suggested by Posner (1973) and later by Clifton et al. (1977). The multiple code hypothesis states that a primary (same modality) code is stored, along with a weaker (opposite modality) associate code. Following the probe, the scanning rates is a function of memory item strength, primary modality items being checked more rapidly than associates. The hypothesis further allows for differences in availability due to rehearsal. However, even though the framework exists for explaining

the superiority of auditory probes in the MR condition, it is not clear why a person would rehearse auditory memory items more than the visual. The error data from the present study indicated practically identical rates for auditory and visual probes; it does not seem reasonable to claim that auditory items were "easier." Certainly this is an area requiring further investigation.

Posner wrote in 1973 that ". . .we have emerged from a period in which almost all emphasis in theories of thought has been upon verbal or linguistic processes. Probably changes in our general culture more than experimental results have led to increased sympathy for nonverbal processes in thought. . . .We need to do much more to understand the contributions of different memory codes, their virtues and pitfalls" (p. 67). Hopefully, the present research has helped to shed a bit more light on this very complex area of human behavior.



## APPENDIX A

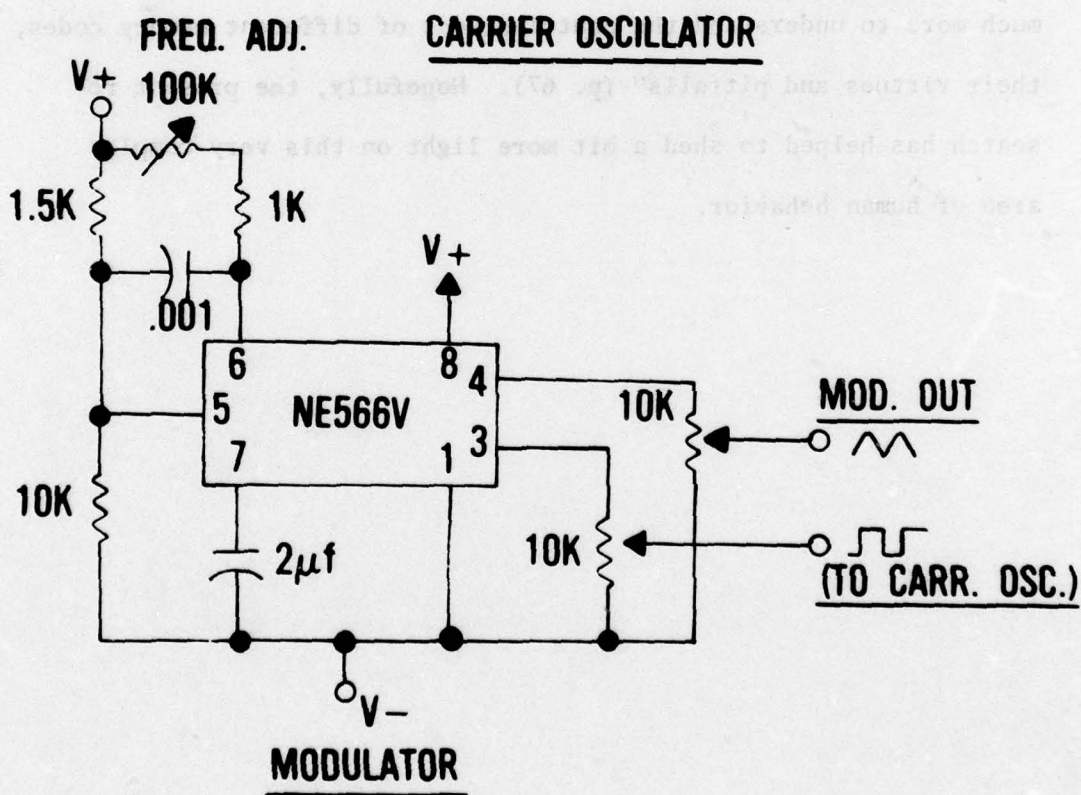
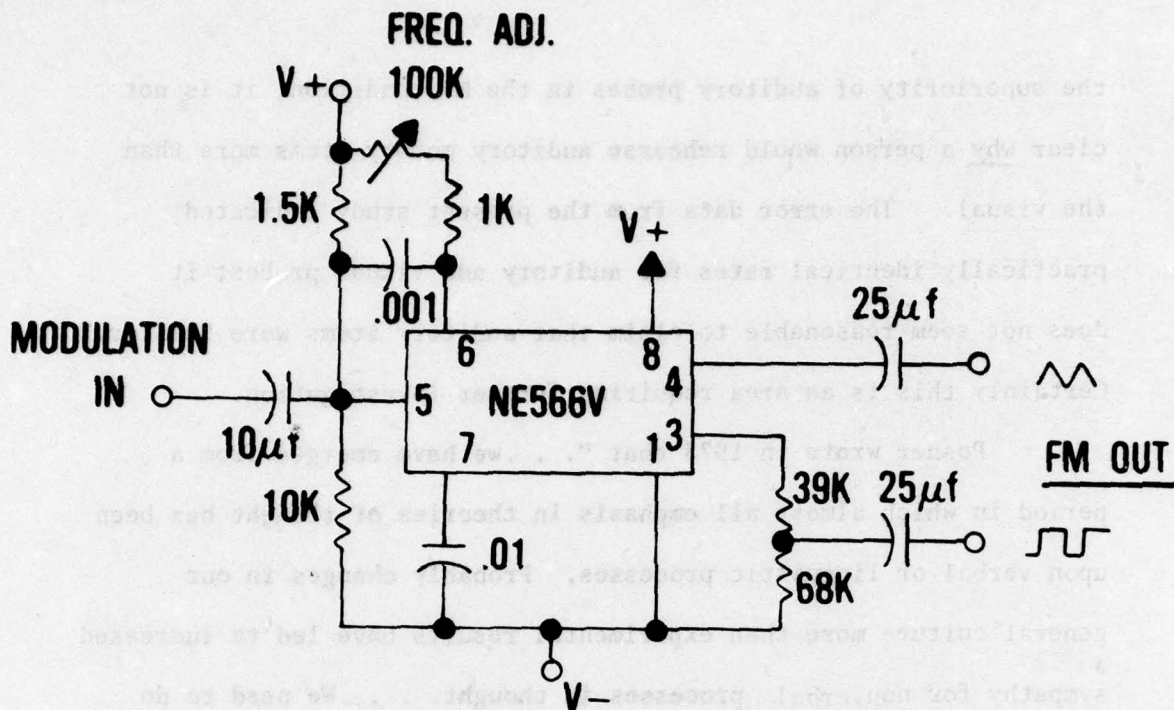


Figure 7. Tone generator schematic diagram.



## APPENDIX B

### INSTRUCTIONS TO SUBJECTS

#### Read the following to all subjects:

The pairs of visual and auditory symbols which you have been learning (hereafter called V-A pairs) will now be used in an experiment whose purpose is to study how visual and auditory information is processed. In this study you will no longer simultaneously see and hear the visual and auditory stimuli which go together. Instead, you will either hear or see from one to four symbols; they will be all visual, all auditory, or a mixture of the two, depending on which part of the experiment you are participating in at the time. This so-called "memory set" will be presented to you one at a time. Your task is to remember these symbols until a single test stimulus is presented about two seconds after the last memory set item. You must then decide, as quickly as possible, with minimum error, whether this test stimulus is the same as any one of the symbols in the memory set. If it is a member of the set, press the right-hand response key; if not, press the key under your left hand. This, basically, is all that will be required throughout this experiment.

Now, this is very important: For the duration of the experiment, the two parts of the V-A pairs you have learned should be considered as exactly the same stimulus, just as the letter F and the sound /ef/ mean the same in English. Therefore, if the visual part of a V-A pair you have learned appears in the memory set and the auditory part appears as the test stimulus (or vice-versa) the correct response is "same" (right hand). Obviously, if it appeared in exactly the same form as in the memory set the answer would also be "same." Otherwise, the left key should be depressed.

#### Read the following at the start of the MI condition:

In this part of the experiment the memory set might be 1, 2, 3, or 4 visual symbols, auditory symbols, or various mixtures of visual and auditory. The test stimulus, if it matches one of the memory set items, can occur in either the same modality as it was originally presented or the opposite modality. In both cases the answer would be "same." Of course, the test stimulus could also be different than any of the memory items, requiring the corresponding response.

#### Read the following at the start of the MR condition:

In this part of the experiment the memory set will contain 1, 2, 3, or 4 items. They can be all visual, all auditory, or a

mixture of the two modalities. The important thing to remember is that, if the test stimulus is the "same" as one of the memory items, it will always be in the same modality as it appeared in the memory set. There will be no exception to this. Thus, for example, if you were shown a combination of two visual and two auditory stimuli to be remembered, and if a visual test stimulus appeared, then you would only have to consider the two visual items from the memory set. That is, you could ignore the auditory items in your memory, since the test item was visual. Conversely, if an auditory test probe had been presented, you would only have to compare it to the two auditory stimuli in memory, ignoring the visual items. If only one visual item and three auditory stimuli were in the memory set, and if the test were a visual item, then you would only have to compare it to the one visual item in memory. Notice I am not relieving you of the necessity for deciding if the test stimulus is the same or different from the relevant memory items. That is, the test item still may not match any of the items in the same modality in memory. Your response in this case would, of course, be to signal a non-match by pressing the left key as quickly as possible with minimum error. In the special case where you have only to remember a single stimulus which is, for example, auditory, and then if a visual test probe appears, your response would be "different" (the left-hand key). The response in this case should be practically automatic; i.e., it should require no conscious thought at all. If the test probe were auditory, then you would still have to make a "same" or "different" judgement as before. Also, there can be trials where all the memory items and the test probe are in the same modality; in such cases you must, of course, consider all the items before making your response.

For the most part, however, your task can be made easier if you use the modality information as has been described. There will be no tricks; the test item, if it matches one of the memory items, will always be in the same modality.

Read the following to all subjects:

The ratio of "same" to "different" stimuli will always be about 50-50, so do not press one of the response keys until you have seen (or heard) the test stimulus and have made your decision. As always, you should try to do this as quickly as possible while avoiding errors. It is normal to have a few errors in a task of this type, but with care on your part they can be held to a minimum. Do not get flustered if you realize you have just made a mistake; forget it, relax, and concentrate on the next set of stimuli which appears.

Are there any questions?



# APPENDIX C

## EXPERIMENTAL DESIGN

MI Condition (Mixed Sets)

s	A				V			
	s	p	n	n	s	p	p	n
2								
3								
4								

Mixed  
Memory  
Set

MR Condition

s	A				V			
	s	p	n	n	s	p	p	n
1								
2								
3								
4								

Mixed  
Memory  
Set

MI Condition (Pure Sets)

s	A				V			
	s	p	n	n	s	p	p	n
1								
2								
3								
4								
1								
2								
3								
4								

A

Memory  
Set

V

Note. A and V indicate auditory and visual items, respectively. N = 8; 20 replications per subject.



## REFERENCES

- Adams, S. A., and Dijkstra, S. Short-term memory for motor responses. Journal of Experimental Psychology, 1966, 71, 314-318.
- Brandt, W. E., Jr. Program documentation for the bimodal short-term recognition memory program (AMRL-TR-76-36). Wright-Patterson Air Force Base, Ohio: 6570 Aerospace Medical Research Laboratory, Human Engineering Division, April 1976. (NTIS No. A-025 745)
- Briggs, G. E., and Johnsen, A. M. On the nature of central processing in choice reactions. Memory & Cognition, 1972, 1, 91-100.
- Burrows, D. Modality effects in retrieval of information from short-term memory. Perception & Psychophysics, 1972, 11, 365-372.
- Burrows, D., and Okada, R. Serial position effects in high-speed memory search. Perception & Psychophysics, 1971, 10, 305-308.
- Chase, W. G., and Calfee, R. C. Modality and similarity effects in short-term recognition memory. Journal of Experimental Psychology, 1969, 81, 510-514.
- Clifton, C., Jr., Cruse, D., & Gutschera, K. D. Recoding processes in recognition: Some effects of presentation rate. Memory & Cognition, 1973, 1, 387-394.
- Clifton, C., Jr., Sorce, P., and Cruse, D. The translation effect in memory search. Cognitive Psychology, 1977, 9, 1-30.
- Conrad, R. Acoustic confusions in immediate memory. British Journal of Psychology, 1964, 55, 75-84.
- Crowder, R. G., and Morton, J. Precategorical acoustic storage (PAS). Perception & Psychophysics, 1969, 5, 365-373.
- Cruse, D., and Clifton, C., Jr. Recoding strategies and the retrieval of information from memory. Cognitive Psychology, 1973, 4, 157-193.
- Dainoff, M. J. Time course of visual and auditory encoding. Journal of Experimental Psychology, 1970, 86, 214-224.

- Dumas, J. Scanning memory for multidimensional stimuli with extended practice. Perception & Psychophysics, 1972, 11, 209-212.
- Edwards, A. L. Experimental design in psychological research. New York: Holt, Rinehart, and Winston, 1968.
- Fristoe, M., and Blanton, R. L. Like- and cross-modality recognition at two levels of meaningfulness in short-term memory task. Paper presented at the 78th annual convention of the American Psychological Association, Miami Beach, September, 1970.
- Hann, R. L. The Sternberg paradigm and memory scan research. Unpublished paper, Vanderbilt University, 1973.
- Kirsner, K., and Craik, F. I. M. Naming and decision processes in short-term recognition memory. Journal of Experimental Psychology, 1971, 88, 149-157.
- Murdock, B. B., Jr. Where or when? Modality effects as a function of temporal and spatial distribution of information. Journal of Verbal Learning and Verbal Behavior, 1969, 8, 378-383.
- Neisser, U. Cognitive psychology. New York: Appleton, 1967.
- Peters, G. L. Coding processes in active and inactive memory. Journal of Experimental Psychology, 1974, 102, 423-430.
- Peterson, C. R., and Peterson, M. J. Short-term retention of individual verbal items. Journal of Experimental Psychology, 1959, 58, 193-198.
- Posner, M. I. Abstraction and the process of recognition. In G. H. Bower and J. T. Spence (Eds.), The psychology of learning and motivation (Vol. 3). New York: Academic Press, 1969.
- Posner, M. I. On the relationship between letter names and superordinate categories. Quarterly Journal of Experimental Psychology, 1970, 22, 279-287.
- Posner, M. I. Coordination of internal codes. In W. G. Chase (Ed.), Visual information processing. New York: Academic Press, 1973.
- Posner, M. I., Boies, S. J., Eichelman, W. H., and Taylor, R. L. Retention of visual and name codes of single letters. Journal of Experimental Psychology Monograph, 1969, 79 (1, Pt. 2).



- Posner, M. I., and Keele, S. W. Decay of visual information from a single letter. Science, 1967, 158, 137-139.
- Posner, M. I., and Konick, A. F. Short-term retention of visual and kinesthetic information. Organizational Behavior and Human Performance, 1966, 1, 71-86.
- Posner, M. I., and Mitchell, R. F. Chronometric analysis of classification. Psychological Review, 1967, 74, 392-409.
- Smith, E. E. Choice reaction time: An analysis of the major theoretical positions. Psychological Bulletin, 1968, 69, 77-110.
- Sperling, G. A. A model for visual memory tasks. Human Factors, 1963, 5, 19-31.
- Sternberg, S. High-speed scanning in human memory. Science, 1966, 153, 652-654.
- Sternberg, S. Two operations in character recognition: Some evidence from reaction-time measurements. Perception & Psychophysics, 1967, 2, 45-53.
- Sternberg, S. Memory-scanning: Mental processes revealed by reaction-time experiments. American Scientist, 1969, 57, 421-457.
- Sternberg, S. Memory scanning: New findings and current controversies. Quarterly Journal of Experimental Psychology, 1975, 27, 1-32.
- Swanson, J. M., Johnsen, A. M., and Briggs, G. E. Recoding in a memory search task. Journal of Experimental Psychology, 1972, 93, 1-9.
- Teichner, W. H., and Krebs, M. J. Laws of visual choice reaction time. Psychological Review, 1974, 81(1), 75-98.
- Theios, J., Smith, P. G., Haviland, S. E., Traupmann, J., and Moy, M. C. Memory scanning as a serial self-terminating process. Journal of Experimental Psychology, 1973, 97, 323-336.
- Townsend, J. T. A note on the identifiability of parallel and serial processes. Perception & Psychophysics, 1971, 10, 161-163.
- Tversky, B. Pictorial and verbal encoding in a short-term memory task. Perception & Psychophysics, 1969, 6, 225-233.



- Vanderplas, J. M., and Garvin, E. A. The association value of random shapes. Journal of Experimental Psychology, 1959, 57, 147-154.
- Vinglis, E., Blake, J., and Theodor, L. Recognition vs. recall of visually vs. acoustically confusable letter matrices. Memory & Cognition, 1977, 5, 146-150.
- Wickelgren, W. A. Speed-accuracy tradeoff and information processing dynamics. Acta Psychologica, 1977, 41, 67-85.
- Wood, L. E. Modality-specific coding in matching letters. Perception & Psychophysics, 1977, 21, 329-335.
- Young, M. E., and Juola, J. F. Stimulus-form effects in recognition memory. Memory & Cognition, 1977, 5, 131-138.